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Vacuum Sewer Systems

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VACUUM SEWER SYSTEMS

by

DAVID W. AVERILL AND GARY W. HEINKE

prepared for

Northern Science Research Group
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and Northern Development

September 1974

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Key to Symbols, Abbreviations, Terminology, and Units

1. SYMBOLS

A = cross-sectional area (ft^2)
C_1 = the ratio of pipe cross-sectional area (A) to bubble cross-sectional area (A_b) (see equation 10, Chapter 3)
C_f = Fanning friction factor
= $f/4$
C'_f = two-phase homogeneous friction factor
D = pipe diameter (ft.)
f = friction factor
G = mass flux ($slugs/sec/ft^2$)
= W/A
g = acceleration due to gravity
= $32.2\ ft/sec^2$
h_L = headloss (feet of water)
j = volumetric flux ($ft^3/sec/ft^2$)
= Q/A
L = pipe length (ft.)
L_g = length of air bubble (ft.)
L_l = length of liquid plug (ft.)
N = number of persons served
N_R = Reynolds number
p = pressure (lb/ft^2) (psf)
$\frac{dp}{dz}$ = pressure gradient ($lb/ft^2/ft$) (z measured along pipe centreline)
Q = volumetric flow rate (ft^3/sec)
q_m = mean volumetric flow rate (GPCD)
s = plug spacing (ft)
= $L_g + L_l$
V = velocity of liquid (ft/sec)
ν = volume (ft^3)
υ = specific volume (defined as volume per unit mass) ($ft^3/slug$)
W = mass flow rate (slugs/sec)
= $Q\rho$
x = quality
γ = air-to-water ratio
= L_g/L_l
δ = surface film thickness (ft.)
Θ = angle to vertical; wedge angle
μ = dynamic viscosity ($lb.\ sec/ft^2$)
ρ = density ($slugs/ft^3$)
τ = shear stress (lb/ft^2) (psf)
$\varnothing^2$ = two-phase multiplier

Subscripts
b = bubble
d = design
F = frictional
G = gravitational
g = gas (air)
l = liquid (water)
m = mean

2. ABBREVIATIONS

amp = ampere
°C = degrees centigrade
cfs = cubic feet per second
cm = centimetre
fps = feet per second
ft = feet
GPCD = Imperial gallons per capita per day
GPD = Imperial gallons per day
GPM = Imperial gallons per minute
hr = hour
kg = kilogram
kw = kilowatt
kw-hr = kilowatt-hour
l = litre
m = metre
MGD = Million Imperial gallons per day
mm = millimetre
NTP = normal temperature and pressure (20°C, 760 mm Hg)
psf = pounds per square foot
psi = pounds per square inch
sec = second

3. TERMINOLOGY AND UNITS

The terms "discharge valve" and "wastewater admittance valve" are used more or less interchangeably to describe the same units. Their usage depends on the context in which they are applied; that is, wastewater is admitted to vacuum mains but discharged from vacuum toilets or buffer tanks. Some sources of information use the name "evacuation valve" rather than "discharge valve".

Some sources of information use the terms "diaphragm valve" and "piston-type valve" in a confusing manner. This report distinguishes between a piston-type valve, which uses a rubber sleeve (not diaphragm), and a diaphragm valve which uses a flexible rubber diaphragm (or membrane). This distinction becomes apparent in the text.

The terms "plug-flow" and "slug-flow" also appear to be used interchangeably. Most sources of information about the vacuum sewer system refer to "plug-flow", whereas the principal source of information on flow theory refers to "slug-flow". This report generally uses the term "plug-flow" when referring to the transport mechanism in vacuum pipes, except where the use of quotations makes the alternate terminology necessary. In addition, it is often convenient to refer to "slugs" of air and "plugs" of water when discussing vacuum transport.

The British Engineering System of Units is used exclusively in this report (foot, pound, second, slugs mass). All volumes are expressed in Imperial units; metric units of length and volume are also included, except in calculations.

Preface

This is a report on the study of vacuum sewer systems and their potential applications in Canada, particularly in the Canadian Arctic. The text is divided into four parts: a general description of the system; an analysis of an existing installation and its operation; a brief study of vacuum transport theory and design practices; and suggestions concerning possible Canadian applications of the system.

The vacuum transport of wastewater is a relatively new technique which has received little publicity in many parts of the world. Chapter I describes the basic principles and characteristics of the system and the various components used.

Chapter II is primarily concerned with a large vacuum sewer installation in the Bahamas. Since first-hand experience with vacuum sewers is the best way to understand the operational and maintenance aspects, David Averill spent six weeks working with government crews at a vacuum sewer installation in Nassau. Vacuum sewers have been operating in the Bahamas and in other parts of the world for several years. The Bahamas were chosen in preference to other locations, partly because of financial and communications considerations, but primarily because it was known that the government-owned installations there were being renovated to overcome operational problems. This situation provided an excellent opportunity for studying vacuum sewer systems.

Chapter III presents a brief, and admittedly incomplete, survey of the theory of vacuum transport and the design practices employed.

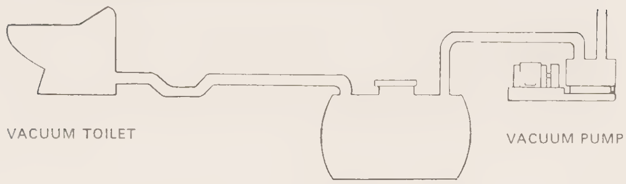
Chapter IV considers the possible applications of vacuum sewers in Canada. It was originally intended to include in this report a preliminary design of a Canadian Arctic installation; however, such a project would be somewhat premature at this time. The need for further investigations, primarily concerning cost estimates and heating-insulation requirements, will require more time. Also, the advent of an American vacuum sewer installation in Alaska may make the postponement of a similar Canadian installation advantageous.

Much of the information presented herein has been obtained through the courtesy of the developers of the vacuum system. All design criteria and figures presented in this report are for illustrative purposes only and are not necessarily representative of the techniques and specifications currently used by those organizations.

The bulk of the work reported here represents part of the requirements for the Degree of Master of Engineering undertaken by David Averill under the supervision of Dr. Heinke. The resulting thesis was completed in January, 1973, and was subsequently used as a draft for this report. The draft was then revised and updated following its distribution to various people and organizations possessing experience with vacuum sewer systems.

Summary and Recommendations

1. The Vacuum Sewer System



The vacuum sewer system is an advanced method of wastewater transport which utilizes air pressure rather than gravity as the driving force. Vacuum sewers carry plugs of wastewater (separated by air gaps) at high velocities through small diameter pipes, utilizing a pressure differential of about one-half atmosphere which is created by partially evacuating the pipe network. Wastewater enters the vacuum system through specially-designed vacuum toilets and wastewater admittance valves, both of which are operated by the vacuum in the system. The wastewater is then transported through the pipe network to a vacuum collection tank. The collected wastewater then may be either pumped from the collection tank, or removed by a scavenger truck, for transport to a suitable treatment facility.

2. Applications

The vacuum sewer system has been used successfully in Scandinavia since 1959 and in other parts of the world since 1965. It has been applied to single-family housing developments, apartments, luxury hotels, cottage communities, schools and other institutional buildings, and has been used on ships and trains, and in portable sanitary facilities. The vacuum system was introduced in Canada late in 1972.

By mid-summer of 1973 there were two marine installations and three trailer-mounted portable units in operation in Canada. A third marine installation and two more trailers were under construction in addition to three permanent land-based installations. Vacuum sewers probably will be applied predominantly in areas where conventional sewer systems would be difficult and expensive to build.

One significant potential use is for arctic community services.

The vacuum sewer system is flexible as it can be applied in several different types of installations and modified to suit existing conditions and sanitary requirements. Toilet wastes (black water) can be transported by vacuum in black water vacuum systems while all other household wastewater (grey water) is either transported in a separate grey water vacuum system or disposed of by conventional methods. Combined sewage may be transported in a one-pipe vacuum system utilizing either conventional water closets or vacuum toilets. Vacuum transport inside buildings is possible with the use of both vacuum toilets and grey water vacuum valves placed near the fixtures served. The size of a vacuum sewer installation may be as small as a single-family house or cottage, or as large as a residential subdivision or village. Towns and cities may be serviced by using several vacuum collection systems, or vacuum systems may be integrated into conventional municipal systems to service certain buildings or neighbourhoods.

3. Advantages and Disadvantages of Vacuum Sewer Systems

Advantages:

1. *save water:*

Vacuum toilets use about one quart (1.2 litres) of water per flush as compared to conventional water closets which use two to four gallons (10 to 18 litres). This represents a considerable water saving.

2. *reduce sewage volume:*

The quantity of domestic wastewater is reduced by 30 per cent to 40 per cent by the use of vacuum toilets. This results in reduced volumetric loadings in sewers, holding tanks, and sewage treatment plants.

3. *reduce cost of sewer construction:*

Since vacuum sewers can transport wastewater horizontally and to a certain extent up-grade, the depth of sewer excavations may be reduced in many cases. The savings achieved in excavation costs may be considerable, particularly where rock excavation and dewatering operations may be avoided. Also, where the topography is essentially horizontal it is possible to eliminate many of the lift stations normally required with conventional sewer systems. Vacuum sewers can be built with long sections of small-diameter light-weight plastic pipe. Sewer construction therefore can proceed rapidly and economically using a minimum amount of heavy equipment.

Similarly, vacuum sewers, when applied to utilidors in arctic areas, simplify construction and reduce costs.

4. *simplify plumbing systems:*

The small diameter pipes used for vacuum wastewater transport can be placed inside walls and floors. By combining the ability to carry wastewater horizontally and vertically, small pipe sizes reduce plumbing costs and help to simplify building design. Sanitary fixtures therefore may be located in various parts of buildings without the constraints imposed by gravity-flow piping; this advantage is of particular importance in building renovation projects.

5. *overall costs savings:*

Vacuum sewer systems in Europe and the Bahamas

were constructed for about two-thirds the capital costs of equivalent conventional sewer systems. The primary saving results from the use of small-diameter plastic pipe in relatively shallow trenches instead of the larger diameter vitreous or concrete pipes which often require deeper excavations and several pumping stations to maintain gravity flow.
The maintenance costs of vacuum sewer systems apparently are at least as low as those of comparable conventional systems.

6. *flexibility:*
Black water systems, grey water systems, and one-pipe systems may be chosen to suit various requirements.

7. *leak-proof sewers:*
Pollution or contamination of ground and surface waters can be practically eliminated by the use of vacuum sewers. There is little possibility of anything leaking out of a vacuum sewer because if vacuum pipes are cracked or joints poorly sealed, air or groundwater would leak into them. It therefore may be possible to instal water mains and sewers in one trench and further decrease construction costs.

8. *advanced wastewater treatment:*
The separation of black and grey waters made possible by the vacuum sewer system permits the use of advanced methods of wastewater treatment. It may be possible to treat concentrated black water separately in specially-designed treatment plants. Grey water, which is relatively uncontaminated, may be reused after treatment, or treated with the effluent of the black water treatment process.

Disadvantages:
1. *size limitations:*
Air pressure, not gravity, is employed as the driving force in vacuum sewer systems. The available pressure differential is limited to about 0.7 atmospheres; consequently, the amount of headloss which may be generated in any one main is limited. The lift capacity and length of vacuum mains therefore are limited. For example, one-pipe mains are restricted to a lift of about 16½ feet (five metres approx.) and to a length of about 6,000 feet (2,000 metres approx.). However, one vacuum collection station may utilize several mains, and large areas may be serviced by several collection stations.

2. *complexity:*
Vacuum sewer equipment is more complex than conventional sewer equipment and operators will require additional training in its use and maintenance.

4. Recommendations
1. The vacuum sewer system is being developed by private organizations. The components used in the system and certain of its features are patented and the pertinent technical knowledge is protected by the patent-holders (AB Electrolux, Stockholm, Sweden). In order to determine the extent to which the system has been developed and to which it is privately controlled, a patent search is advisable prior to further studies by government or educational institutions.
2. A thorough study of all aspects of hydraulics related to plug-flow should be performed, preferably by an individual with experience in pressure and vacuum systems.
3. Further study is required concerning the application of vacuum sewers to the Arctic. Specific points of interest include the behaviour of plastic pipe in extremely cold temperatures, and the heating and insulation requirements of vacuum sewers (including heat input rates, heat loss rates, and wastewater retention times).
4. Laboratory tests should be performed to study friction headloss, lift capacity, scale formation and removal, as well as heat loss, freezing damage, and the effectiveness of heat-tracing systems.
5. Research should be conducted to determine the most efficient ways to treat vacuum sewer effluents. The system variations may produce concentrated black water, black water plus kitchen wastewater, dilute grey water, conventional domestic sewage, and semi-concentrated sewage (from one-pipe systems using vacuum toilets).
6. Practical Canadian experience with vacuum sewers is essential if costs and system reliability are to be assessed. Therefore, it is recommended that pilot black water systems and one-pipe systems (with and without vacuum toilets) be constructed both in the Arctic and in more southerly locations.

Chapter I

The Vacuum Sewer Concept

1.1 Comparison to Conventional Sewers

The conventional method of collecting and transporting wastewater is by gravity-induced flow. This method has been used for centuries with little change; it is simple, dependable, and usually economical. However, gravity sewers have characteristics which may become disadvantageous under certain conditions. The large quantities of water required, the large pipe sizes, and the constraint of hydraulic grade lines, may pose considerable problems where water is scarce, construction materials expensive, and where topography and soil conditions are not compatible with required grade lines.

Conventional sewers require large volumes of water to transport wastes by gravity-induced flow. The driving force created by small differences in elevation is not sufficient to move concentrated wastewater containing large amounts of settleable solids. Conventional water closets for example, use from 70 to 100 times as much water as the volume of waste transported. Almost half of all domestic wastewater consists of toilet wastes from conventional water closets, while the rest consists of wastewater from sinks, bathtubs, washing machines, etc. It is not practical to substantially reduce the amount of water consumed for cleaning purposes, but a reduction in the amount used to transport toilet waste would be beneficial in terms of the cost of water supply, sewer, and wastewater treatment systems.

Conventional sewer systems produce a large volume of dilute wastewater which is both difficult and expensive to treat. Toilet waste, which contains most of the pollutants and almost all of the contaminants found in household wastewater, is diluted to about 200 times its original volume, first in the transport water, and then in the remaining household wastewater. The waste is diluted in order to transport it to a treatment plant but there it must be concentrated again to obtain a reasonable degree of effluent purity. In order to increase wastewater treatment efficiency it would be beneficial to prevent any unnecessary dilution of toilet wastes by reducing the quantity of water used for transport and/or by separating toilet waste from the rest of household wastewater.

Conventional sewer systems utilize gravity as the transport force and they must be laid mostly along hydraulic grade lines. In favourable locations gravity transport of sewage is not a problem, provided the amount of water required is disregarded. However, where the topography is flat or has an adverse slope, or where rock or groundwater are found near the surface, gravity sewers can become very expensive and difficult to construct.

There are perhaps only two alternatives to gravity wastewater transport: pressure sewers and vacuum sewers. Pressure sewers are, of course, used in conjunction with gravity sewers as force mains and in lift stations; however, completely pressurized sewer systems are currently in the prototype stage of development. Vacuum sewer systems have been in operation for over 10 years and have been proven both reliable and economical.

The fundamental principle of the vacuum sewer concept is the transport of wastewater by air pressure, rather than by the gravity-induced flow of water. Vacuum sewer systems have two distinct advantages over conventional gravity systems: the vacuum system can function by using much less water than gravity systems; and, wastewater transport is not restricted to following hydraulic lines. By utilizing a pressure differential of less than one atmosphere, vacuum sewers can transport wastewater horizontally and, to a certain extent, up-grade. Another advantage of the system is the potential for separating wastewater from toilets and urinals (black water) from the rest of the household wastewater (grey water) and this facilitates efficient treatment methods.

Some locations provide a fortunate combination of ample water supply, adequate natural drainage and the potential for adequate wastewater treatment and disposal. There is little incentive, under those conditions, to replace the conventional type of sewer system. Vacuum sewers probably will be constructed in these locations in Canada only when and if it is demonstrated that a substantial financial saving can be achieved. Vacuum sewer systems will be applied initially in areas which are not ideally suited to conventional systems; that is, where water is scarce and water distribution systems are expensive, and where conventional wastewater systems are both difficult and expensive to build. Communities are emerging in climates and on terrains where conventional systems simply cannot function. Modifications to the gravity system, such as the use of utilidors in the Arctic, have been useful to some extent; however, further development along conventional lines is not likely to overcome the inadequacies of the gravity-flow system.

It could be argued that discarding a simple system, which utilizes natural forces, in favour of a technically more complex system is not a desirable step. However, with developing technology man has a proven record of discarding systems which rely on natural forces in favour of those which depend on mechanization and generated energy. Mechanization of utilities has enabled man to live in relative comfort under existing crowded conditions and without grossly polluting the environment. As there has been an acceptance of technical systems as the suppliers of heat, light, communications, and water, there is no reason to reject the concept that another utility,

wastewater disposal, should become mechanized. Furthermore, since vacuum sewers probably will be used as an alternative to conventional systems primarily in areas where lift stations would be required, the choice is actually between one mechanized system and another.

Any advanced wastewater disposal system should possess the following characteristics:

1. reduction of construction costs;
2. reduction of operational costs;
3. reduction of water consumption;
4. production of an acceptable effluent;
5. user acceptability; and
6. flexibility

The vacuum sewer system has been used in Scandinavia since 1959 and in the Bahamas since 1965. It has demonstrated that, at least under certain conditions, it meets all of the above requirements. The following sections in Chapter I describe the vacuum system and its applications.

1.2 Introduction to the Vacuum Sewer System

The vacuum sewer system was invented in Sweden by Mr. J. Liljendahl. Originally called the Liljendahl Vacuum Sewage System, it was employed first in 1959. While the system was owned by its inventor, several installations were completed in Scandinavia, Mexico, Israel, and the Bahamas. The system rights later were sold to the Environmental Systems Division of AB Electrolux of Sweden,[1] and the system became known alternatively as the Electrolux Vacuum Sewage System, the Electrolux Vacuum Sewerage System, and the Sanivac System. Since then, other installations have been established in Australia, Germany, Italy, The Netherlands, Greece, Spain, Yugoslavia, France, the United States and Canada. The Electrolux group of companies have set up demonstration units in several other locations including Switzerland, Brazil and the Canary Islands. The exclusive representative of AB Electrolux in the United States is now Colt Industries.[2] Formerly these rights were held by the National Homes Construction Corporation, which marketed the vacuum system through its Airvac Division.[3] Airvac has made considerable developments in the one-pipe system, and is currently marketing it in the United States. In Canada the vacuum system rights were acquired in 1972 by Vacusan Systems Limited.[4]

The vacuum sewer system is not actually a single system but a group of systems which may be utilized in various ways to meet different requirements. The wastewater from toilets and urinals (black water) may be transported by vacuum in a "black water system" while all other household wastewater (grey water) is transported by conventional methods. Alternatively, the grey water also may be transported by vacuum in a separate "grey water system". When used together the black water and grey water systems form what is called a "two-pipe system". Another version is the "one-pipe system" which conveys all wastewater by vacuum in the same pipe.

The black water system consists essentially of a vacuum toilet, a vacuum sewer (usually of plastic pipe), a collection tank, and a vacuum pump (Fig. 1.1). The vacuum pump, which is controlled automatically, provides a vacuum of about one-half atmosphere (7½ psi; 0.515 kg/cm²) in the system. The vacuum toilet contains a discharge valve which is activated during the flushing operation. It opens for three seconds and allows the wastewater (black water) to be pushed into the pipe by atmospheric air. Black water, in the form of a "liquid plug", is forced rapidly by the air along the pipe toward the collection tank where the air is evacuated from the system by the vacuum pump. The collected wastewater is disposed of intermittently from the tank by sewage pumps or is removed by a scavenger truck. The black water then may be treated in a conventional treatment plant or in a plant specially designed to treat the concentrated waste.

The vacuum toilet uses less than one quart (1.2 litres) of water per flush as compared to the two to four gallons (10 to 18 litres) used by conventional water closets. The water is used primarily for cleaning the bowl because very little is required to transport solid wastes in vacuum mains.

When the vacuum toilet discharge valve opens, the wastewater is pushed into the vacuum pipe by atmospheric air and a quantity of air (2.8 to 4.2 cubic feet; 80 to 120 litres) enters the pipe behind the sewage. This creates a pressure differential in the pipe which transports the waste toward the collection tank. The resulting friction which occurs between the liquid plug and the pipe wall eventually breaks down the plug. The air which was trapped behind the plug then breaks through it and is evacuated from the system. To re-form the plug, the pipe is fitted with "transport pockets" at certain intervals and the wastewater flows by gravity to these pockets during non-transport periods. Once the liquid plug has been re-formed in the transport pocket an increase in the upstream pressure, created by the admission of air to the system at some point up-stream, causes the plug to be transported further down the pipe until it again breaks down. The transport of wastewater in vacuum pipes therefore is intermittent rather than continuous. Transport takes place when a sufficient pressure differential forms across a plug of wastewater. The distance of transport is dependent upon the pressure differential in the main, the size of the liquid plug, the pipe gradient, the pipe roughness and size, and

[1] AB Electrolux, Environmental Systems Division, Stockholm, Sweden, S-105 45

[2] Colt Industries, Power Systems Division, 701 Lawton Avenue, Beloit, Wisconsin, U.S.A., 53511

[3] AIRVAC/Div. National Homes Construction Corporation, P.O. Box 109, Rochester, Indiana, U.S.A., 46975

[4] VACUSAN Systems Limited, 117 Dolomite Drive, Downsview, Ontario, Canada.

the number of bends and other obstructions in the pipe.

Grey water may be transported separately by vacuum in the two-pipe system (Fig. 1.2) or it may be combined with the black water in a one-pipe system (Fig. 1.3). Handbasins, sinks, bathtubs, etc., are usually connected by conventional gravity plumbing. At the lower end of the gravity system a wastewater admittance valve (grey water valve) transfers the grey water to a vacuum main. The wastewater then proceeds toward the collection tank in the form of liquid plugs as described above. Grey water valves may be installed outside the buildings being serviced, often in conjunction with ventilated buffer tanks. Where vacuum transport of grey water inside the buildings is required, the valves may be located near each fixture or group of fixtures served.

A variation of the one-pipe vacuum system is used to carry wastewater from buildings equipped with conventional internal plumbing (Fig. 1.4). This method overcomes transport problems which would be difficult to avoid using conventional gravity sewers, but it does not change the quantity or characteristics of the wastewater. A wastewater admittance valve is installed at the end of the gravity service lateral or mounted on a ventilated buffer tank; in some cases existing septic tanks may be converted for use as buffer tanks.

1.3 Principal Applications

1.3.1 *Introduction:*

The vacuum sewer system is flexible as it can be applied in several different types of installations and modified to suit existing conditions and sanitary requirements. The installation size may be as small as a single-family house or cottage or as large as a residential subdivision or village. Towns and cities. may be serviced by the use of more than one vacuum collection system, or they may be integrated into conventional municipal systems to service certain buildings or neighbourhoods. The vacuum system may be applied to single dwelling units, groups of houses, office buildings, apartments, hotels, industrial estates, and new towns, as well as schools, hospitals, and other institutional buildings. Its advantages are best utilized when a complete vacuum system is installed in a new development, but also it may be advantageously combined with existing conventional plumbing systems and treatment plants. Vacuum systems may be used for the renovation of buildings of all types. Other uses include portable toilet facilities (in trailers or portable buildings) for public gatherings and the construction industry. They have also proven successful when used in ships and on trains.

Black water systems, two-pipe systems, and one-pipe systems may be applied in different ways to meet the particular requirements of each type of installation.

The three general characteristics of the vacuum sewer system are vacuum wastewater transport, limited water usage with the resulting production of concentrated black water, and separation of black and grey waters. Flexibility in the type of vacuum system which may be used permits the utilization of these characteristics to the best advantage in every situation. For example, the separation of grey and black waters, plus concentration of the black water, permit the use of efficient chemical processes for black water treatment. Where conventional treatment is used, separation of the wastes is no longer important, but the water savings and non-gravity transport inherent in the vacuum system are still beneficial.

The following descriptions indicate the various ways in which the vacuum sewer system may be applied to meet different requirements. The list of applications is not intended to include every possibility, but it describes the most probable uses of vacuum sewers.

1.3.2 *Black Water Systems:*

1.3.2.1 *Black water holding system with conventional grey water disposal:*

In this system (Fig. 1.5) black water from the vacuum toilet is transported by vacuum pipes to a collection tank which acts as a holding tank. Sewage is then removed from the tank periodically by a scavenger truck and taken to a nearby gravity sewer or sewage treatment plant. The grey water is collected and treated conventionally at the site. This system produces a relatively small quantity of wastewater which must be trucked away and it eliminates the danger of contamination of local soil and water by pathogenic microorganisms. This technique is particularly suited to isolated areas not served by a sewer system where infiltration of grey water is permitted by the local conditions. It is advantageous for individual homes or cottages, for small housing developments and multi-storey buildings, and for sanitary facilities in parks and camping areas.

1.3.2.2 *Complete black water system with conventional grey water disposal:*

The cost of trucking large volumes of black water makes the system described in section 1.3.2.1 applicable only to developments of limited size. In larger developments it is preferable to treat the black water on the site. Grey water may be infiltrated separately near each point of origin or it may be collected by gravity for treatment in one or more septic tanks. This system, shown in Figure 1.6, may be applied in isolated housing developments (including single-family homes, multi-storey apartments, or cottage communities) where it is possible to discharge treated wastewater to the soil.

1.3.2.3 *Complete black water system with conventional grey water collection and combined treatment:*

This system, shown in Figure 1.7, is applicable in

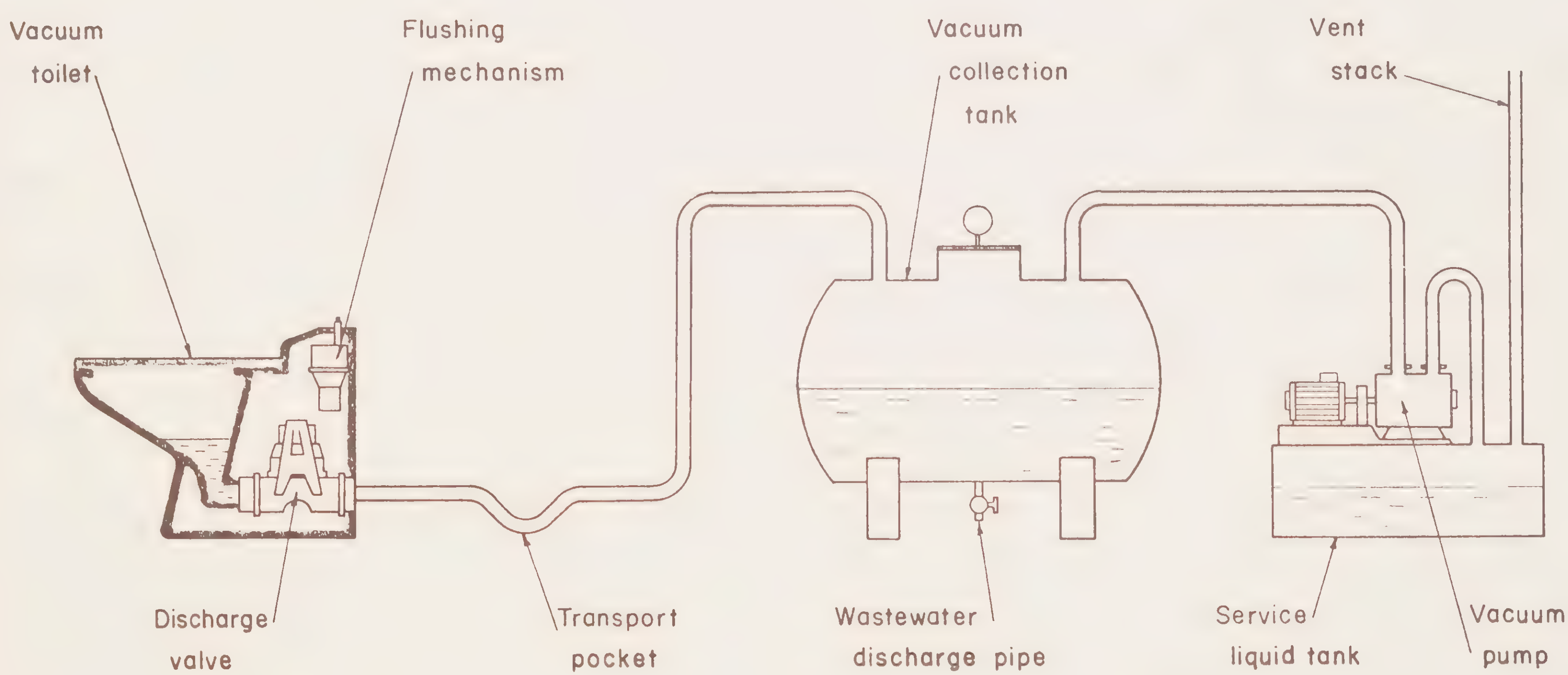


Fig. 1.1 BLACK WATER VACUUM SYSTEM — SCHEMATIC

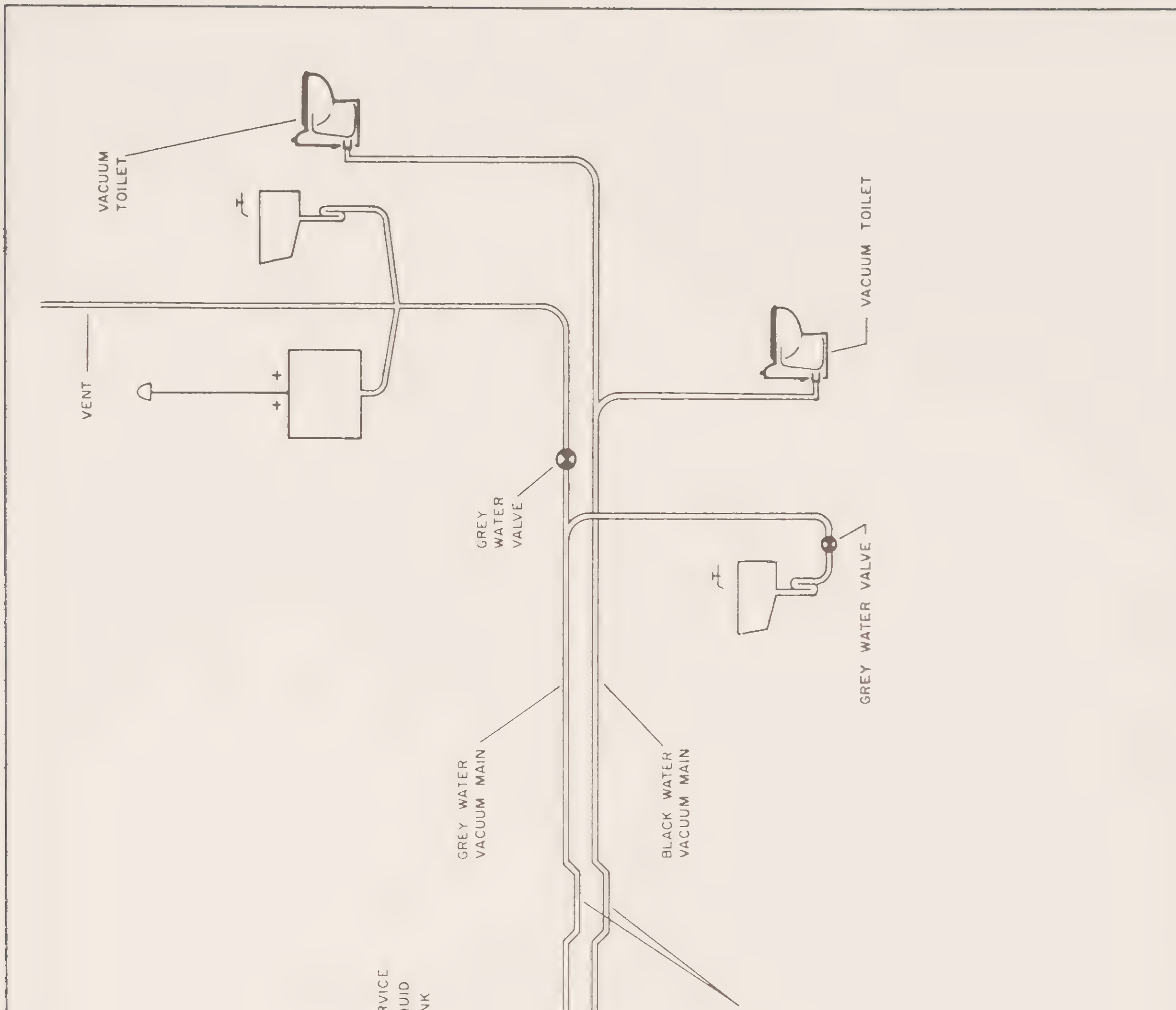


Fig. 1.2 TWO-PIPE VACUUM SYSTEM — SCHEMATIC

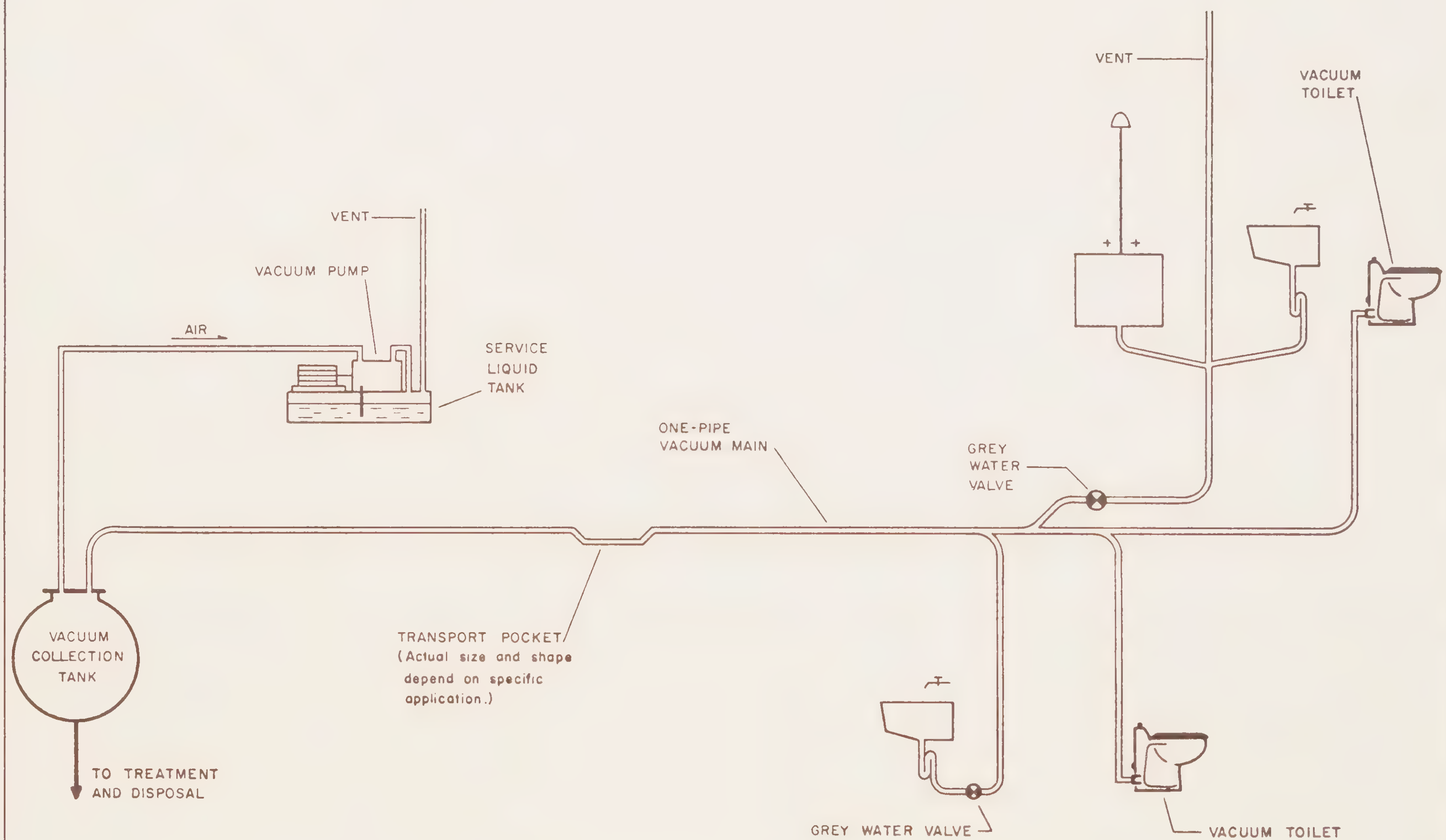


Fig. 1.3 ONE-PIPE VACUUM SYSTEM — SCHEMATIC

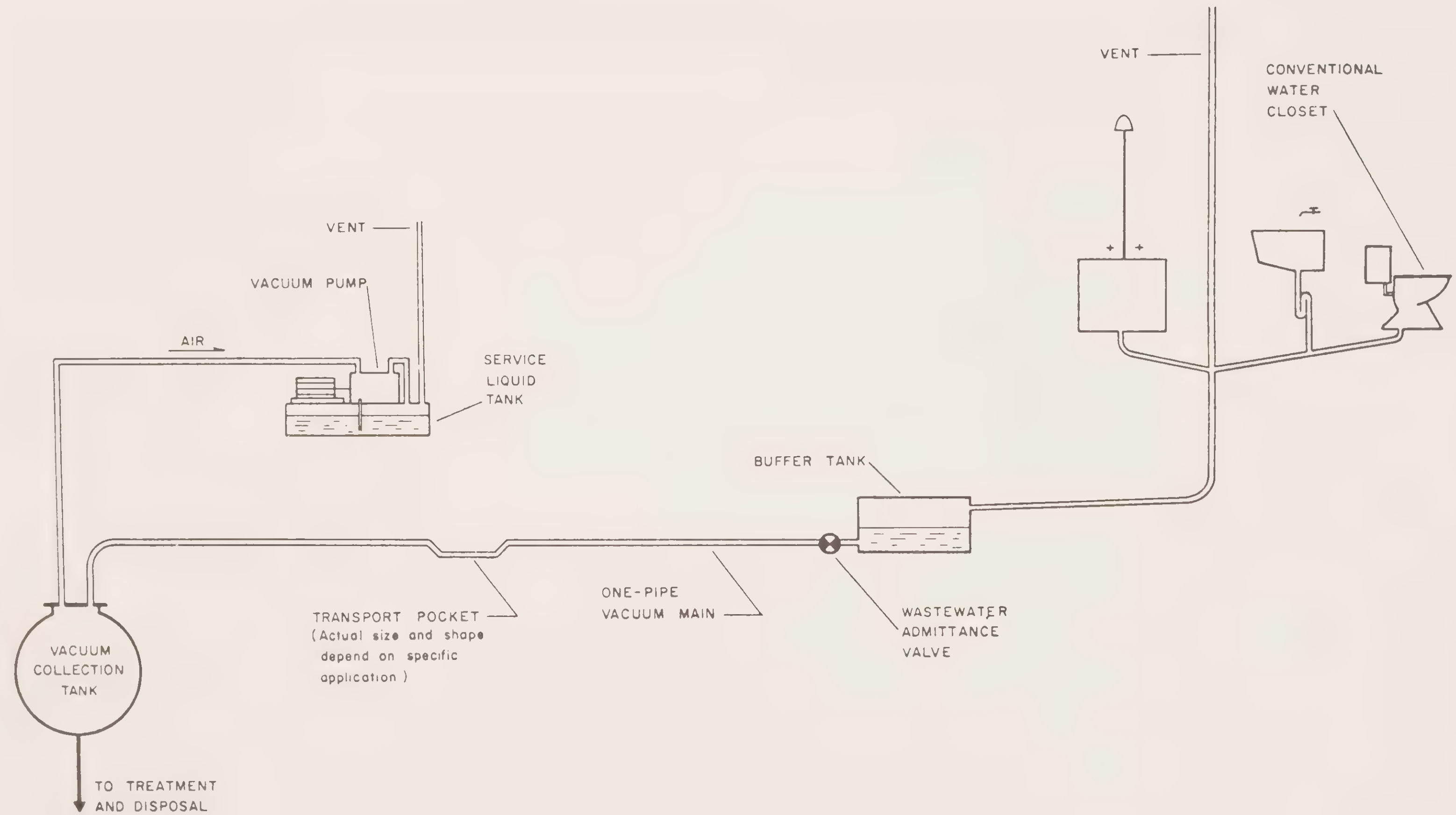


Fig. 1.4 ONE-PIPE VACUUM SYSTEM FOR CONVENTIONAL PLUMBING — SCHEMATIC

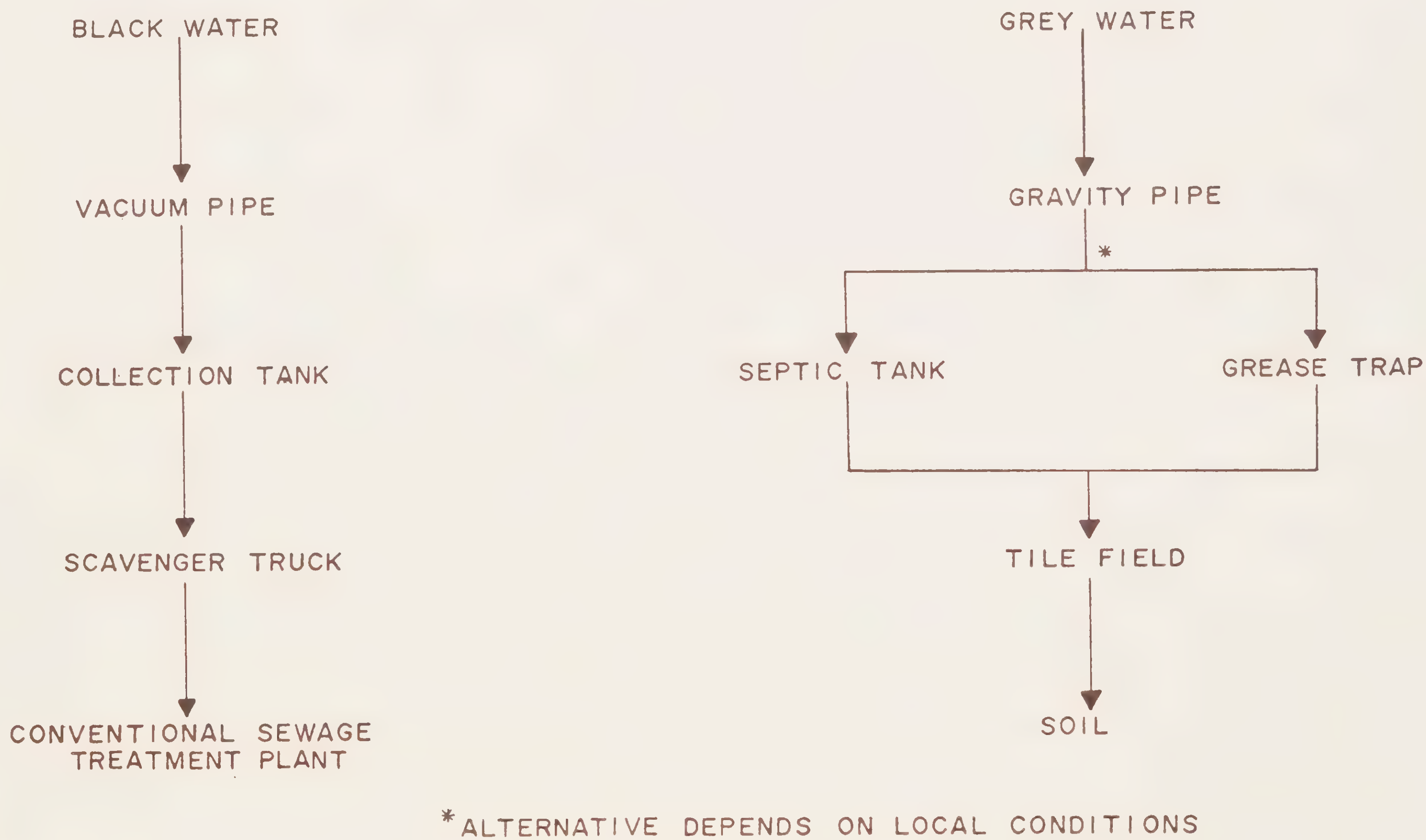


Fig. 1.5 BLACK WATER HOLDING SYSTEM WITH CONVENTIONAL GREY WATER DISPOSAL

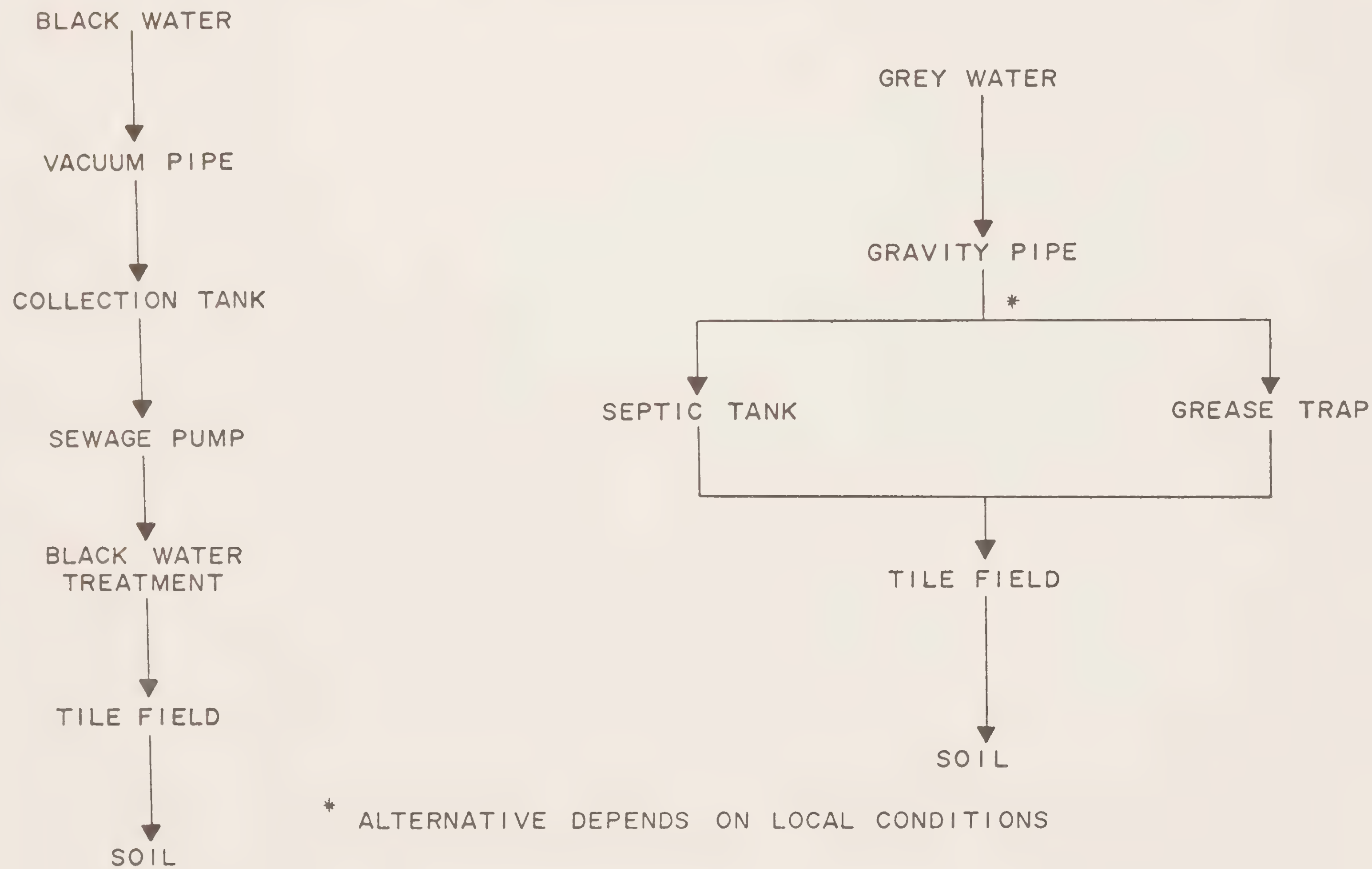


Fig. 1.6 COMPLETE BLACK WATER SYSTEM WITH CONVENTIONAL GREY WATER DISPOSAL

locations where topography and soil conditions permit the use of gravity sewers at a reasonable cost, but where water savings and the separation of black and grey waters for efficient treatment are desirable. In the previous system (section 1.3.2.2) the grey water may be infiltrated in one or more locations throughout the site but, where gravity flow is possible and the size of the development is relatively large, it may be transported by gravity to a central treatment plant. There, it is treated together with the effluent of the black water treatment plant (section 1.6). Effluent from this treatment process may be disposed of directly to a receiving water body. An alternative technique, for locations where gravity transport of grey water is not feasible, is the two-pipe system (section 1.3.3).

1.3.2.4 *Black water systems including kitchen wastes:*

Organic matter may be eliminated from grey water by the inclusion of kitchen wastes in the black water system. The remaining grey water is relatively harmless and may be disposed of directly to soil or water in some locations or may be reused after inexpensive treatment. Reuse of grey water may be of considerable significance in areas where fresh water is extremely scarce. Black water, containing kitchen wastes, may either be collected and trucked away or treated on the site. The quantity of "black water" produced is about 25 per cent of the quantity of wastewater which would be produced by a conventional plumbing system. This system is shown in Figure 1.8. Where trucking is used, the cost of hauling the increased volume of wastewater, plus the cost of the necessary grey water valves, may tend to offset the savings derived from the possible elimination of grey water treatment. However, in systems which use on-site treatment, the cost of treating the additional quantity of wastewater should be marginal.

The combined treatment of black water and kitchen wastewater involves different considerations than with the separate treatment of concentrated black water. The dilution of the combined wastewater is greater than it is in black water, the organic content would be somewhat different, and the presence of detergents in the kitchen wastes may be a significant factor.

1.3.2.5 *Black water collection system with discharge to conventional sewers:*

This system (Fig. 1.9) may be applied where adequate sewers and treatment facilities are available. The advantages are realized in water savings which are made possible by vacuum toilets and the low installation cost of vacuum pipe and fixtures.

1.3.3 *Two-pipe System:*

The two-pipe system (Fig. 1.10) consists of two separate vacuum systems, one for black water and the second for grey water. It may be used where both water scarcity and wastewater transport problems must be overcome. An additional advantage of the two-pipe system is the segregation of the grey and black wastes to permit separate treatment.

1.3.4 *One-pipe Systems:*

1.3.4.1 *One-pipe system with holding tank:*

In this system (Fig. 1.11), black water from vacuum toilets is transported to the vacuum collection tank in the usual way. Grey water, collected by either gravity flow or vacuum inside the buildings, is admitted to the same vacuum conduit that carries the black water and is collected in the same tank. The wastewater then is pumped out by a scavenger truck and transported to a local treatment plant or to an existing sewer system. This vacuum technique is suitable for single isolated houses or small groups of houses in locations where the site is too small to warrant its own treatment facility, too far from existing sewers, and where the discharge of any wastewater to local soil or water is not desirable.

1.3.4.2 *One-pipe system with discharge to treatment facilities:*

This one-pipe system (Fig. 1.12) provides the benefits of reduced water consumption and economical wastewater transport in areas where conventional sewers would be too expensive. The collected wastewater may be discharged to a small treatment plant designed to accept the wastewater from one or more vacuum collection systems. Where conventional sewers and adequate treatment systems are available, the collected wastewater may be discharged to the gravity sewers. The potential for vacuum transport of all wastewater inside buildings provides considerable flexibility in the location of sanitary facilities. This aspect is particularly beneficial when the system is applied to industrial installations and building renovations.

1.3.4.3 *One-pipe system with conventional interior plumbing:*

The latest variation of the vacuum sewer system is a method of transporting conventional wastewater from existing housing units (Fig. 1.13). Since water savings are not achieved, the only advantage of this system is its application in areas where topography and/or poor soil conditions make the construction of conventional sewers impractical. In many cases, houses in rural communities and suburban areas were constructed with septic tank treatment systems. This form of treatment is often no longer acceptable, but because of local conditions, gravity sewers can not be installed economically. The one-pipe concept may also be used in other types of installations; for example, at marinas for unloading pleasure-craft holding tanks.

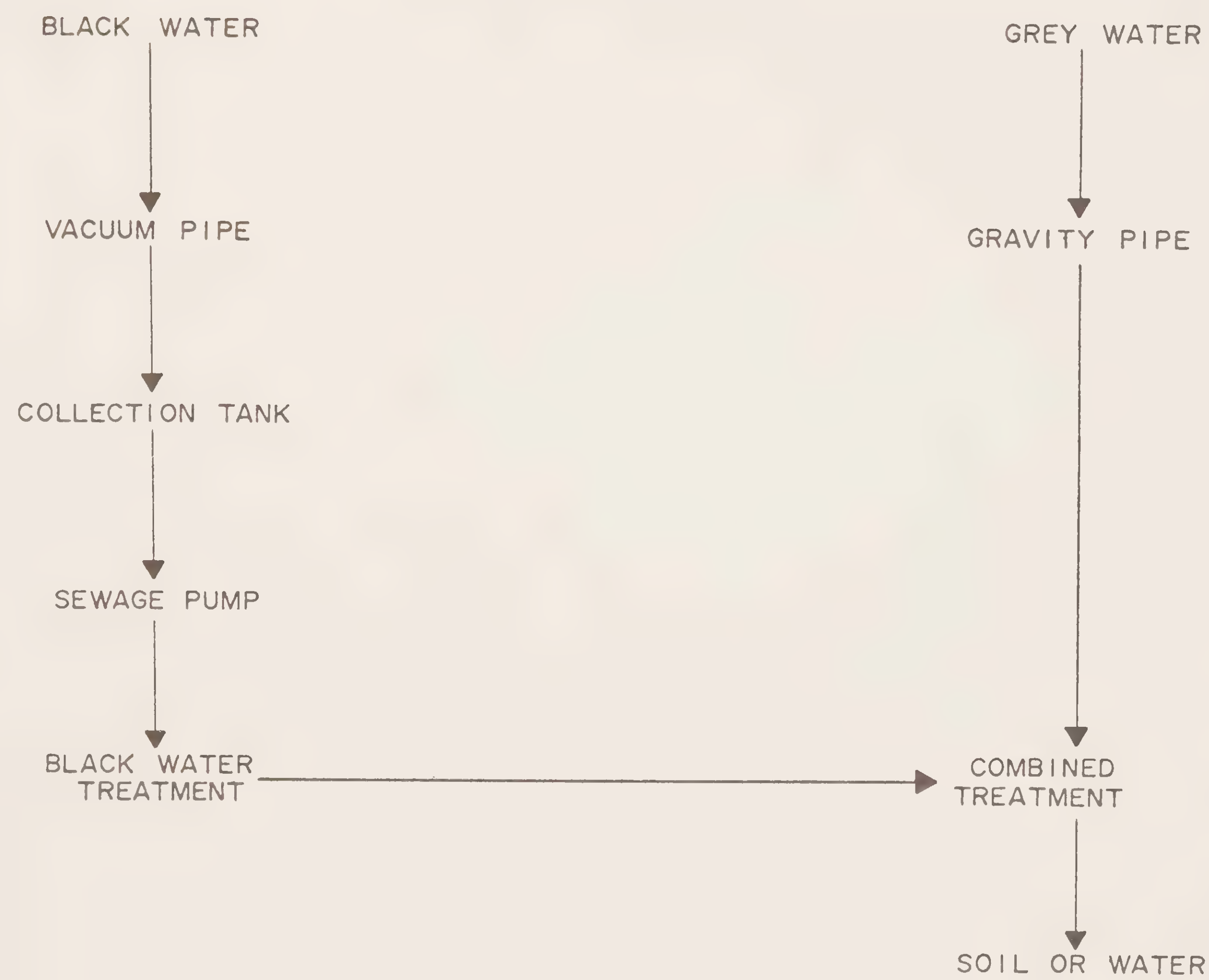


Fig. 1.7 COMPLETE BLACK WATER SYSTEM, CONVENTIONAL GREY WATER COLLECTION, AND COMBINED TREATMENT

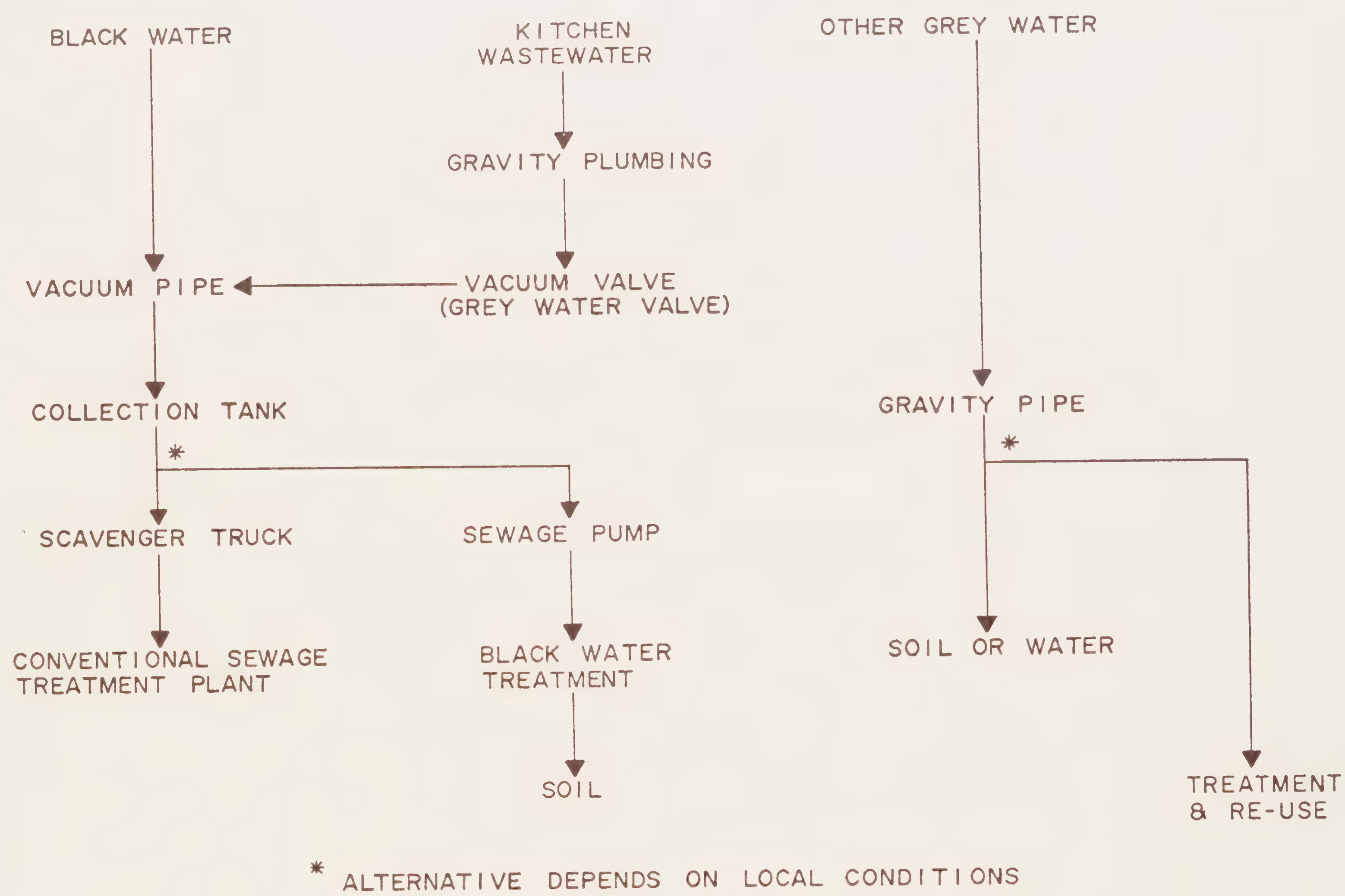


Fig. 1.8 BLACK WATER SYSTEMS INCLUDING KITCHEN WASTES

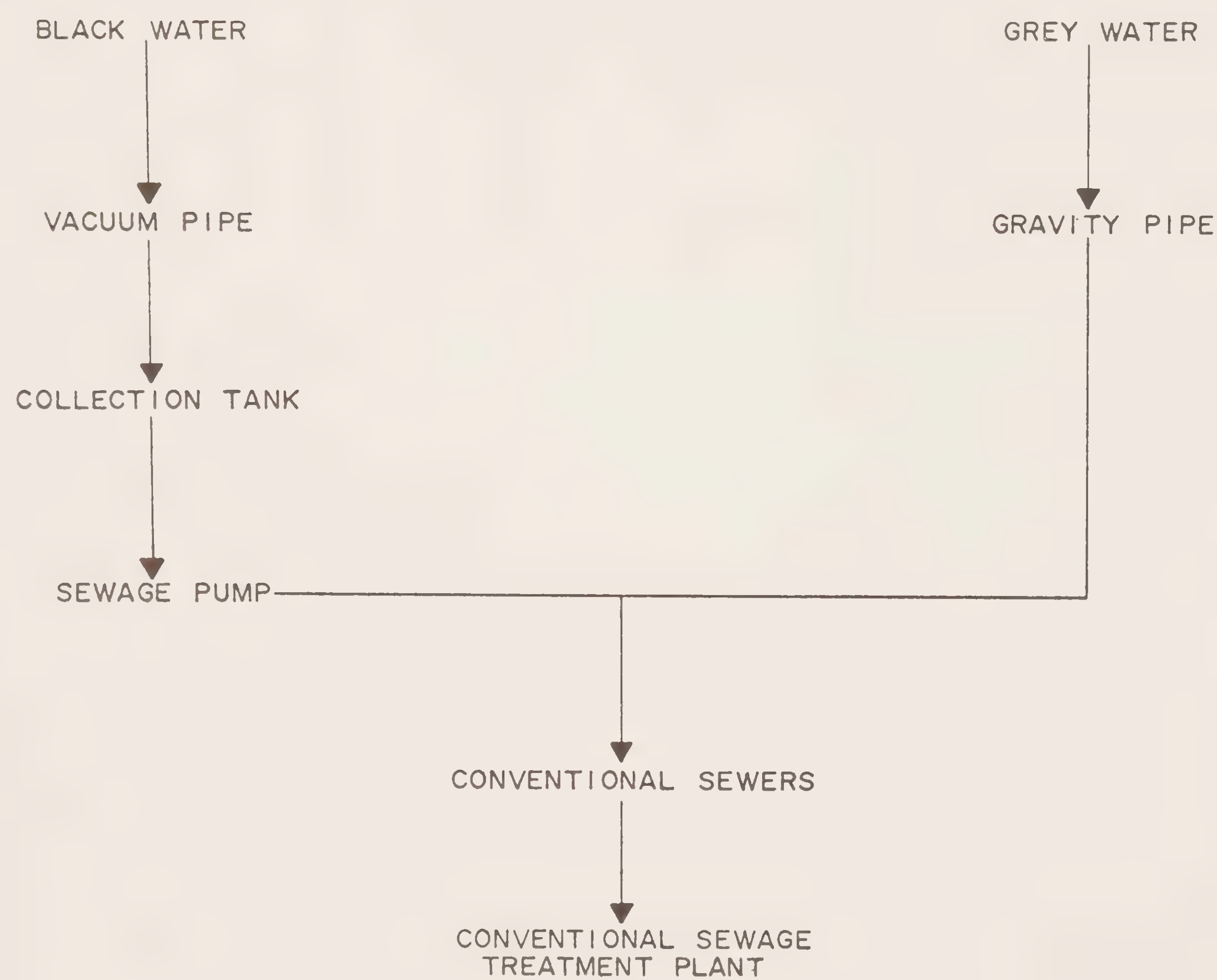
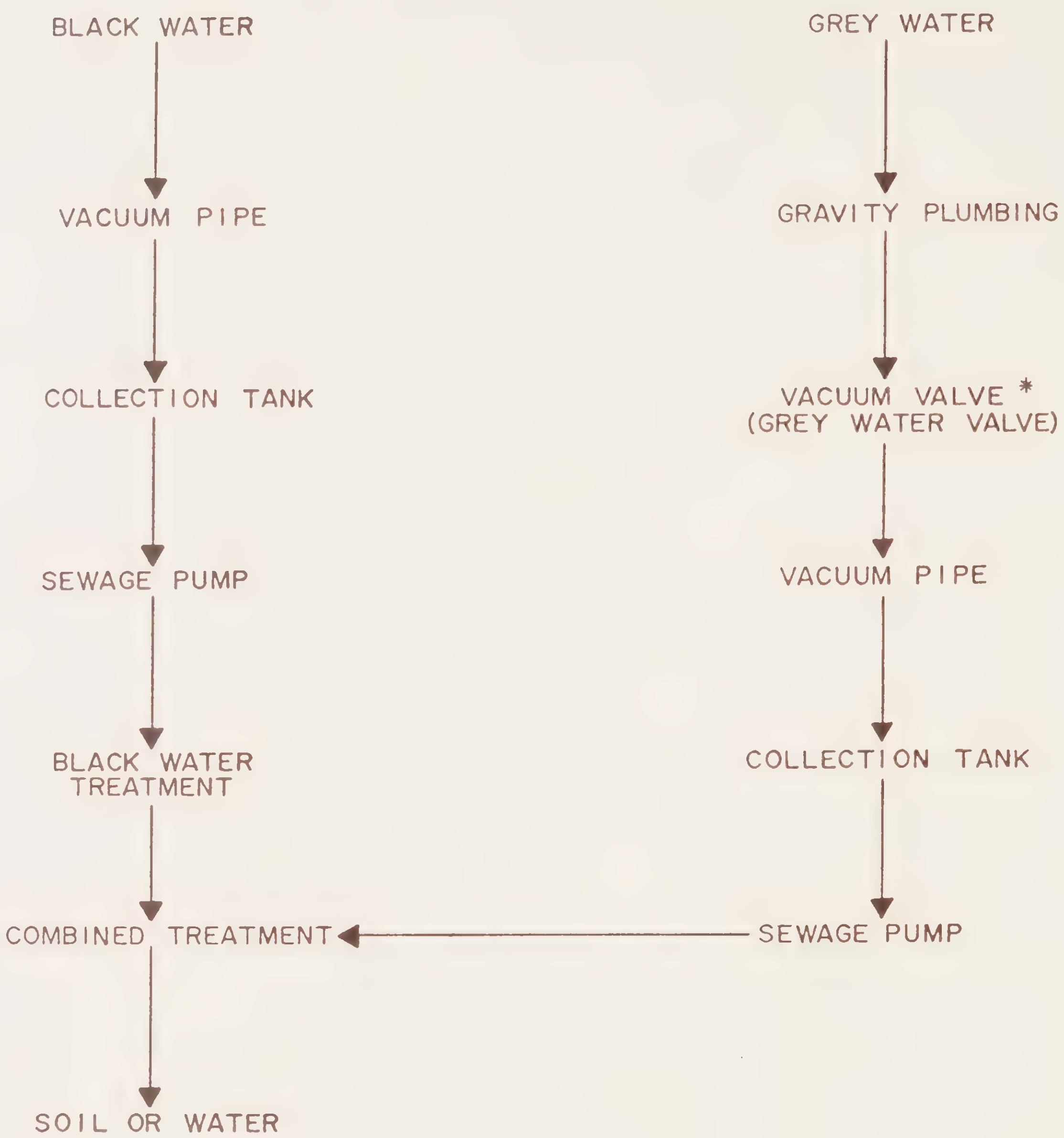


Fig. 1.9 BLACK WATER COLLECTION SYSTEM WITH DISCHARGE TO CONVENTIONAL SEWERS



* MAY BE LOCATED OUTSIDE THE BUILDINGS SERVICED, NEAR THE INDIVIDUAL FIXTURES PERMITTING VACUUM TRANSPORT INSIDE THE BUILDINGS.

Fig. 1.10 TWO-PIPE SYSTEM

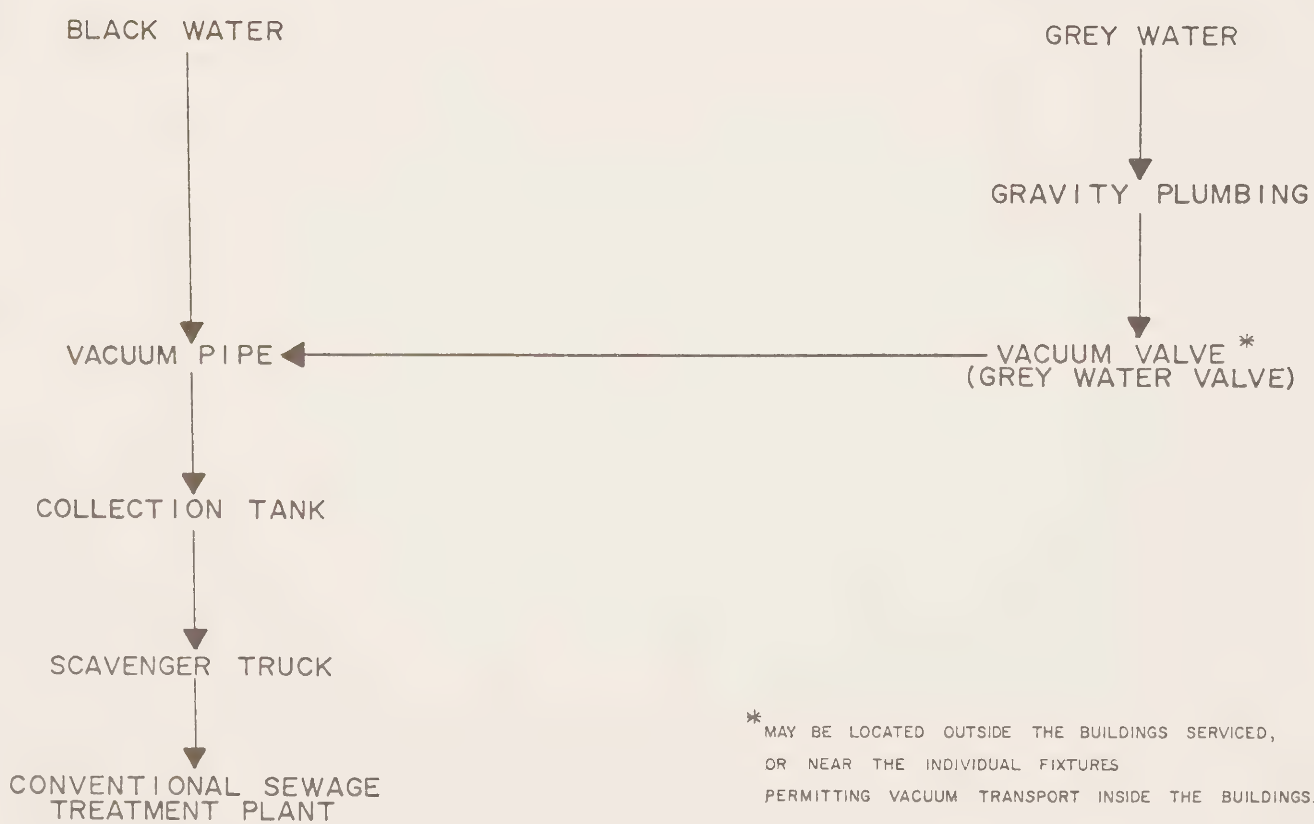


Fig. 1.11 ONE-PIPE SYSTEM WITH HOLDING TANK

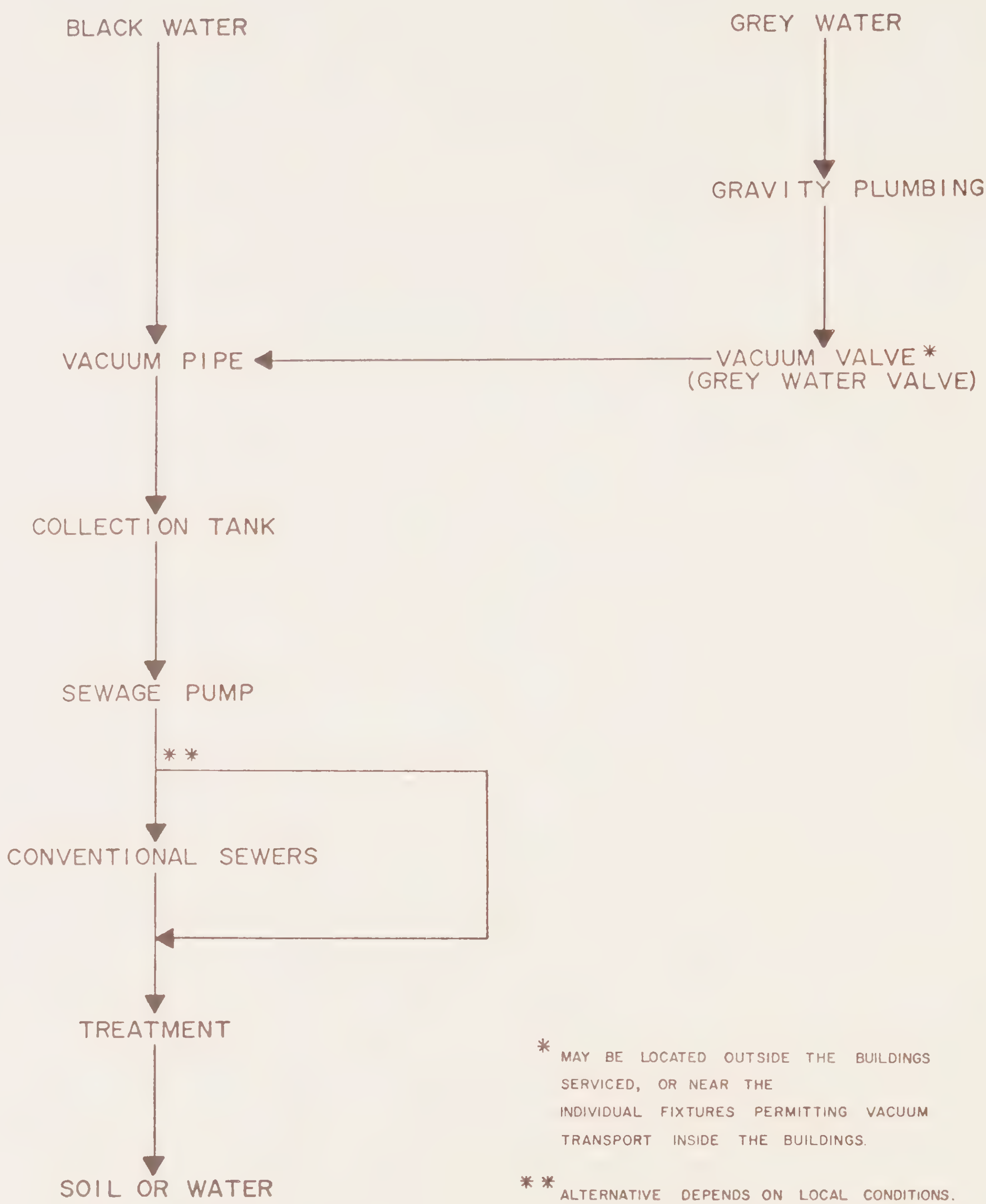


Fig. 1.12 ONE-PIPE SYSTEM WITH DISCHARGE TO TREATMENT FACILITIES

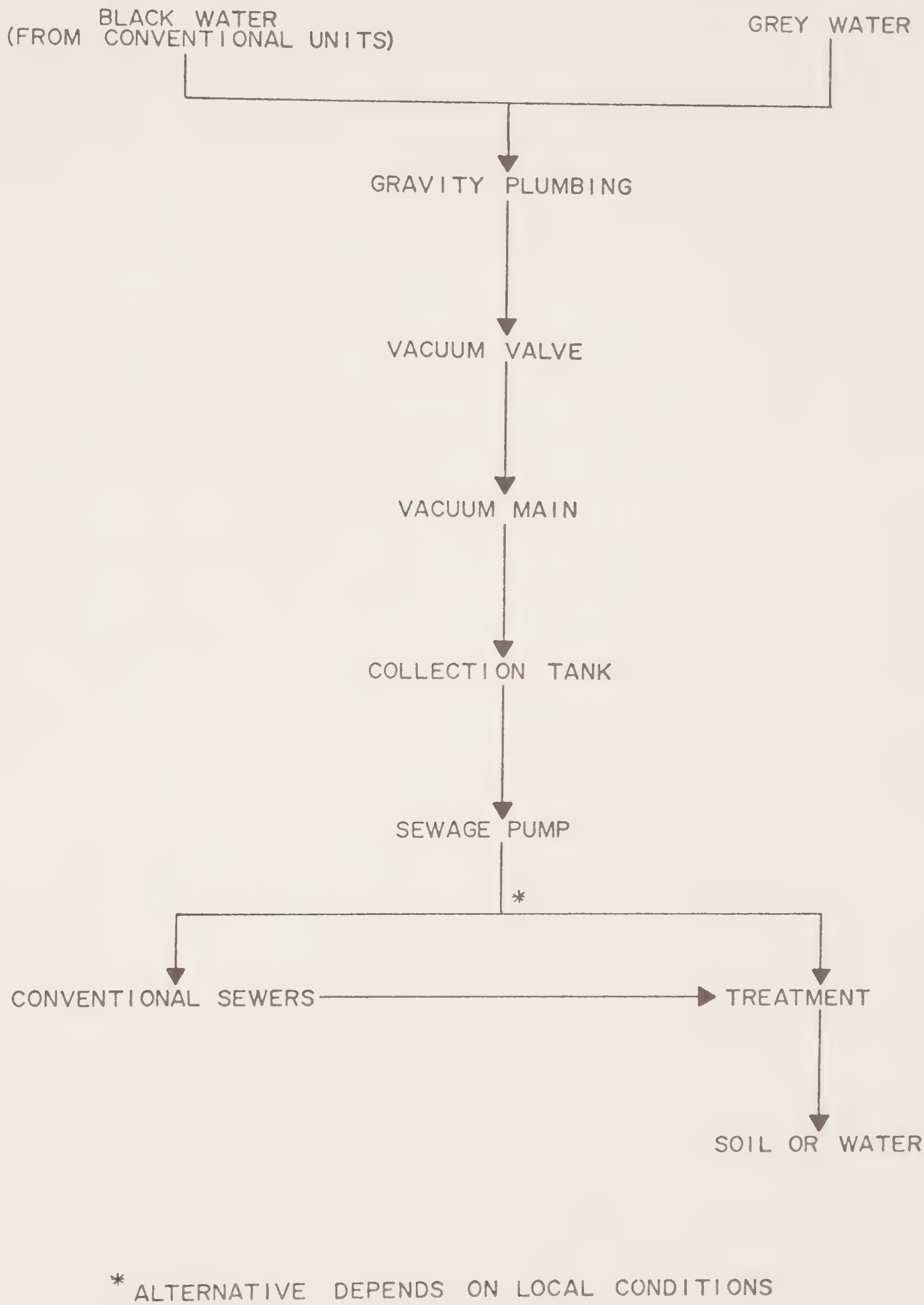


Fig. 1.13 ONE-PIPE SYSTEM WITH CONVENTIONAL INTERIOR PLUMBING

1.4 Description of Components[5]

1.4.1 *Vacuum Toilet:*

The Sanivac toilet (Photo 1.1) is patented worldwide by AB Electrolux of Stockholm, Sweden. Outwardly the vacuum toilet resembles a conventional model; however, the water tank has been replaced by a flushing mechanism hidden at the back of the unit. This mechanism (Photo 1.2) is a mechanical-pneumatic system, made entirely of non-corrodible components, none of which is submerged in water. A discharge valve (Photo 1.3), with a diaphragm of synthetic rubber, connects the toilet bowl to the discharge pipe. This valve, and the water inlet valve, are activated when a starter button is pushed (or pulled, on earlier models). The flushing cycle is controlled by the flushing mechanism; the cycle lasts seven seconds, consisting of three seconds of discharge and bowl rinse, plus four seconds for refilling the bowl. The discharge operation produces more noise than the flushing of most conventional water closets but it is of short duration and apparently has been acceptable to users of the system.

The water inlet valve acts as a check valve preventing contamination of the water supply system and, as a further precaution against back siphonage, a vacuum breaker device may be fitted to it. The toilet discharges into a 1½ inch vacuum line which may be easily hidden inside interior walls. The connection between the discharge valve and a horizontal vacuum pipe utilizes an elastic rubber sleeve, and an elastic rubber 90 degree elbow is used to connect the valve to a vertical pipe. The bowl is attached to the floor by four bolts or wood screws.

The vacuum toilet, illustrated in Figure 1.14, consists of the following components:

1. vitreous bowl (1) which contains a circular 90 degree bend at the discharge end (1⁹⁄₁₆ inch inside diameter);
2. discharge valve (8) connected to the bend of the bowl to separate the bowl at atmospheric pressure from the vacuum pipe at about one-half atmosphere;
3. flushing mechanism mounted on a plastic plate (3) which forms the rear cover of the toilet unit; and
4. water valve (9), controlled by the flushing mechanism, which admits water to the bowl through the water ring (10).

[5]The descriptions of the components of the vacuum sewer system are based partly on personal observations by authors, partly on promotional material published by Electrolux, Livaco, and Airvac (ref. 8, 9, 13, 14, 15, 32, 35, 36), and primarily on draft copies of Electrolux design manuals (ref. 4, 5, 6, 7) and the Sanivac design manual written by National Homes (ref. 37), and the Vacusan Technical Manual (ref. 41).

With the exception of the neoprene rubber used in diaphragms and seals, the vacuum toilet is constructed of materials having a lifetime in excess of 25 years. Some neoprene components have remained operable in excess of nine years. Vacuum toilets have been reported more reliable than conventional water closets (ref. 7).

The following with reference to Figures 1.14, 1.15, 1.16, 1.17, and 1.18, is a brief explanation of the operation of the vacuum toilet:

1. The starter (4) is located at the top of the flushing mechanism with the push button (A27) mounted above the cover (2). When the starter button is pushed down, a continuous passage is created between the vacuum pipe and the discharge timer (7.) Air is drawn out of the discharge timer so that its lower body (C19) is drawn up, compressing the stainless steel spring (C18).

2. When the starter button is released, the stem (A15) of the starter mechanism is held in position by two springs (A21). If there is sufficient vacuum in the system (greater than 0.4 atmosphere vacuum gauge), atmospheric pressure pushes the stem up into its original position, closing the passage between the discharge timer and the vacuum pipe, and allowing air to enter the discharge timer. Air enters the timer slowly through the discharge timer jet (C14) allowing the lower body of the timer to descend slowly. The rate of movement of the timer's lower body may be governed by the selection of the size of the jet. If there is not sufficient vacuum in the system to allow the starter stem to be pushed up, it remains in the lower position, held by the springs, until the system vacuum increases to a sufficient level. In this way the starter automatically stores a "signal" to flush until such time as the vacuum sewer system has a sufficient vacuum level to completely remove the waste. This feature also protects the vacuum mains from becoming overloaded.

3. The discharge timer, as it descends, mechanically trips the vacuum valve (BO3). A passage is then created between the vacuum pipe and both the water timer (6) and the discharge valve (8). Air is simultaneously drawn out of the water timer and the discharge valve. The lower body (C19) of the water timer rises, opening the water valve (9); the lower lifter body (D14) of the discharge valve rises, lifting the rubber diaphragm (D16). When the water valve is opened, water is sprayed into the bowl through the water ring (10). When the discharge valve is opened, the wastewater is pushed into the vacuum line by atmospheric pressure. About 3½ cubic feet (100 litres) of air enters the pipe behind the sewage, setting up a pressure differential which transports the wastewater through the pipe, and ventilating the area around the toilet.

4. Approximately three seconds after the vacuum valve has been tripped, the discharge timer mechanically trips the air inlet valve (BO4). Air then enters

the discharge valve rapidly, stopping the flushing action. Air enters the water timer slowly through the water timer jet (C12); the lower body of the timer takes about four seconds to reach its lower position, at which point the timer mechanically closes the water valve. During that four seconds the bowl receives about 1¼ pints (0.7 litres) of water. When the water valve closes the flushing cycle is complete.

1.4.2 *Pipe Network:*
The pipe used for vacuum sewer lines should have a low coefficient of friction to permit high transport velocities and coherence of the liquid plugs. Plastic pipe is usually recommended and the material may be PVC, ABS, or epoxy-bonded glass fibre. The most common is PVC pressure pipe conforming to metric standard NT10 (10 kg/cm² @ 20°C.) or DWV Schedule 40. PVC pipe sections may be connected by solvent-welded couplings or by rubber ring joints. Solvent welding requires suitable ambient conditions for the creation of air-tight connections and is generally used for interior plumbing and for pre-fabricated pipe sections. Connections made in the field usually involve rubber ring seals. If plastic pipe is not considered satisfactory for some uses, for example, where pipe heating is required or where the pipes pass through bulkheads on ships, galvanized steel pipe may be substituted. However, plastic-lined steel pipe may be preferable because of its low coefficient of friction and its resistance to corrosion. Copper pipe never must be used because it is easily corroded by the ammonia compounds in urine.
Because transport in a vacuum system is by air pressure, and not by gravity, the pipes may be smaller in diameter than those used in conventional systems and they are not restricted to following hydraulic grade lines. The pipe sizes in a typical system include 1½- or two-inch interior plumbing and service laterals, two- or three-inch secondary mains, and where necessary four-or six-inch primary mains. As mains may be laid horizontally, or to a certain extent up-grade, deep cuts can be eliminated. Also, manholes are not needed along the mains; clean-outs spaced at regular intervals along the mains are all that is required.
Pipe fittings must be of the long turn (long radius) type, to reduce headloss and to limit the possibility of blockages. Valves used in vacuum lines must have straight full bores equal to the pipe size. The recommended type of shut-off valve is the Saunders-type KB diaphragm valve, although for large pipe sizes gate valves may replace diaphragm valves. The check valves used in vacuum pipes are flap-type units with rubber-sealed flaps; check valves for pipes up to three-inch diameter are made of PVC and larger units of cast iron.

Photo 1.1 SANIVAC VACUUM TOILET

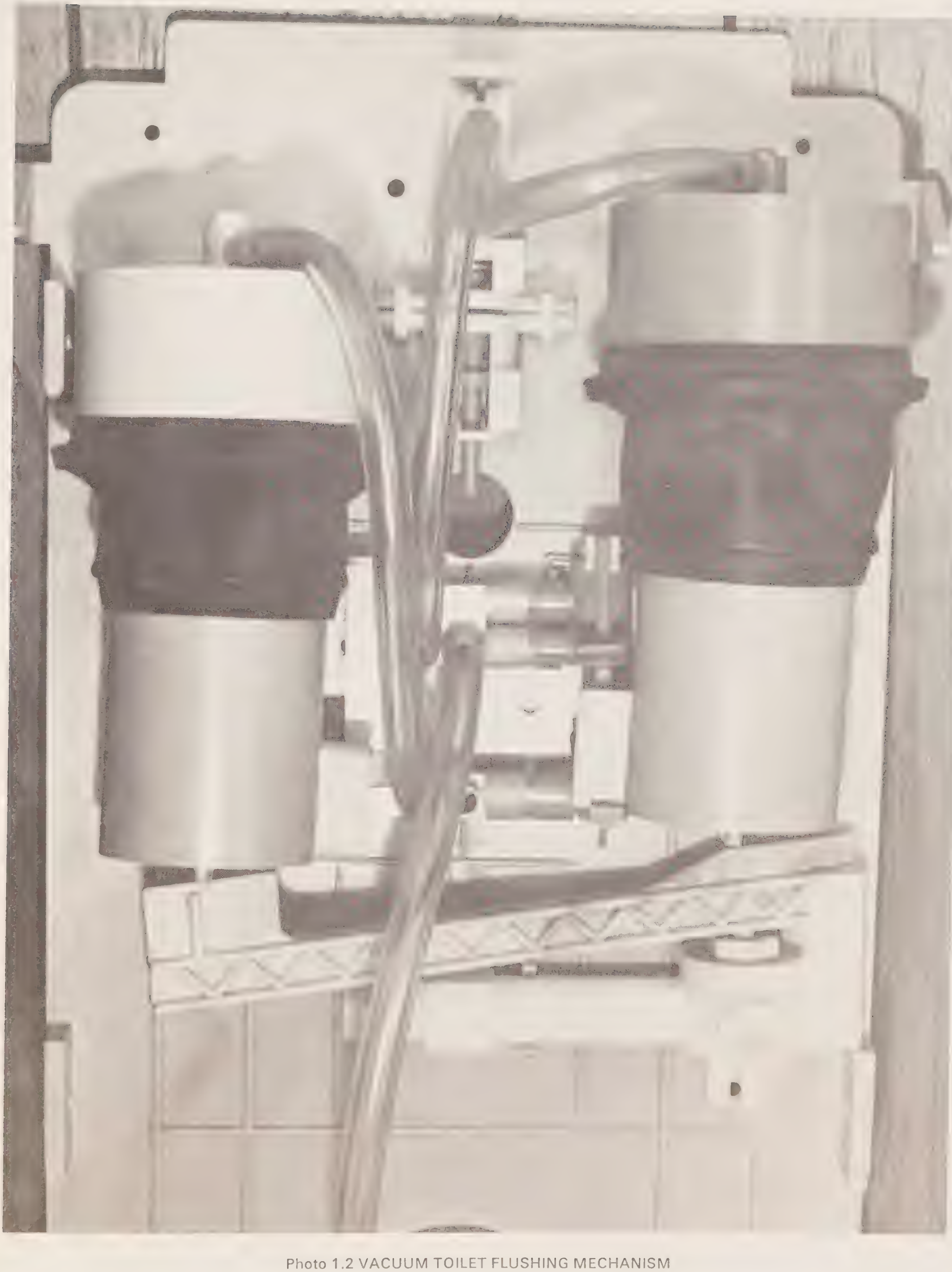


Photo 1.2 VACUUM TOILET FLUSHING MECHANISM

Photo 1.3 REAR VIEW OF VACUUM TOILET SHOWING DISCHARGE VALVE

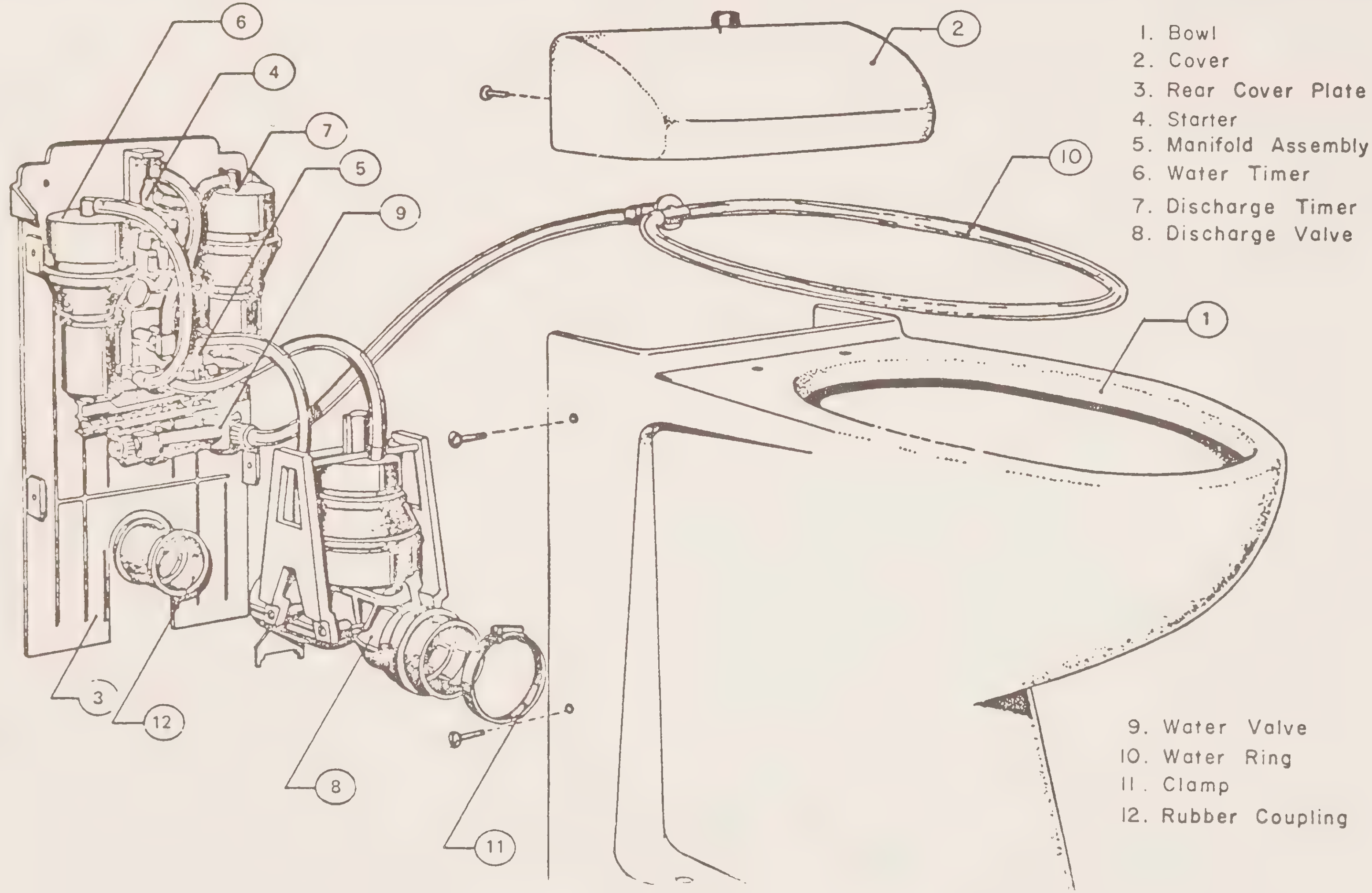


Fig. 1.14 VACUUM TOILET ASSEMBLY

Part No.	Req'd	Part name
A15	1	Stem
A16	1	Washer
A17	1	Rubber seal
A18	1	Rubber collar
A20	2	Nut
A21	2	Spring
A22	4	Pin
A23	1	Hose 7/12 x 125 mm
A24	1	Body
A25	1	Lever arm
A26	1	Push plate
A27	1	Push button
A02		Starter assembly, parts A15 through A18 incl.; and A20, A21, A22, A24, A25

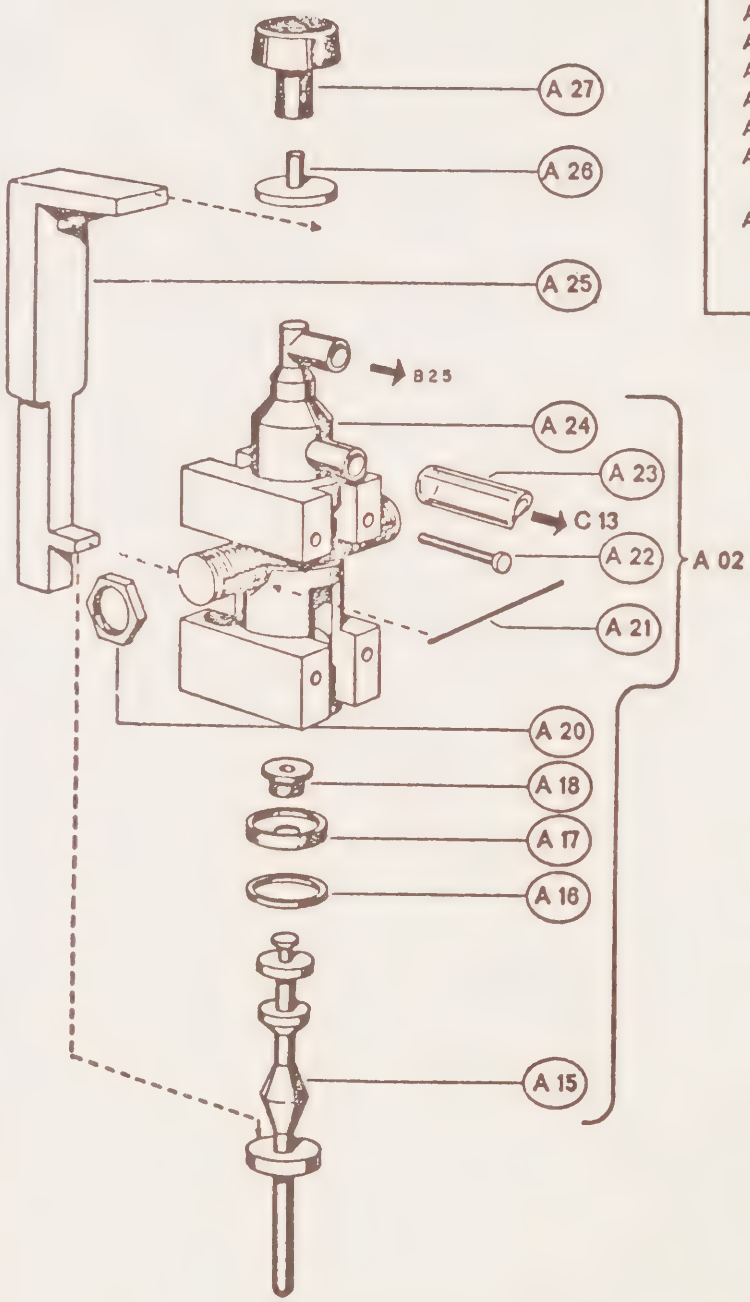


Fig. 1.15 STARTER MECHANISM

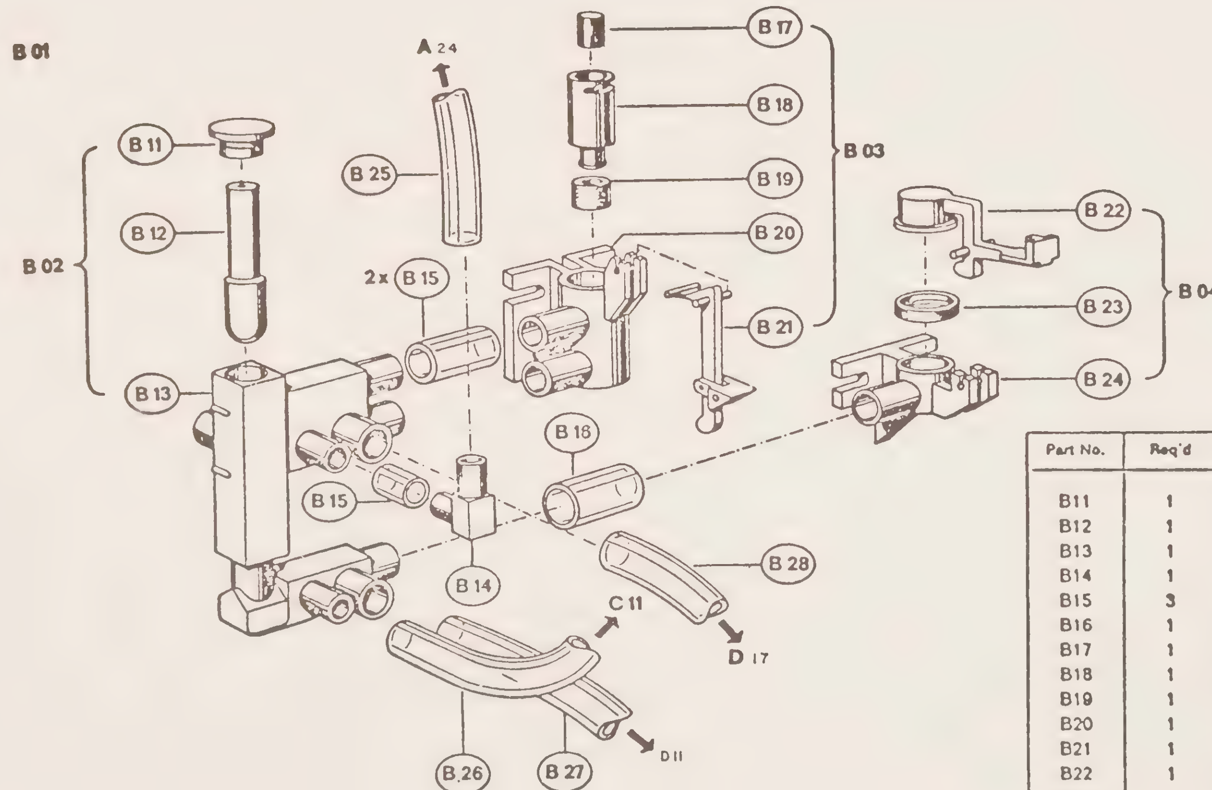
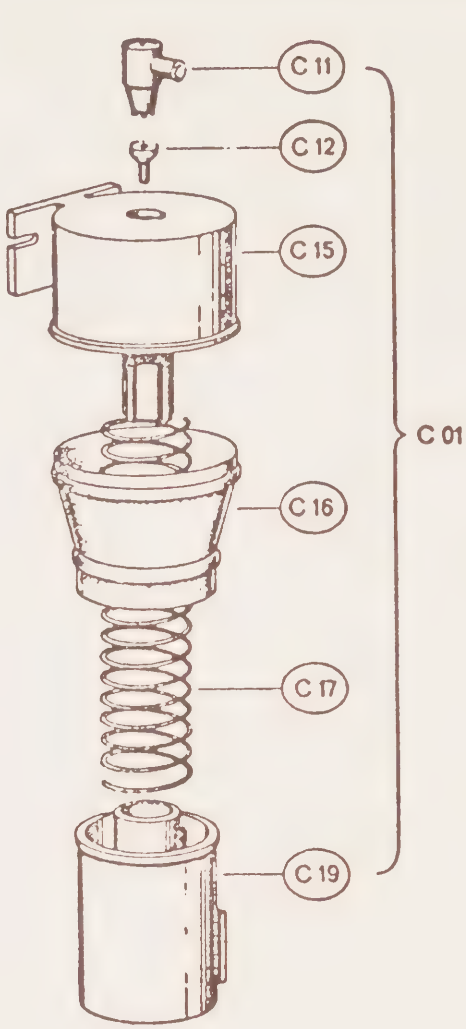
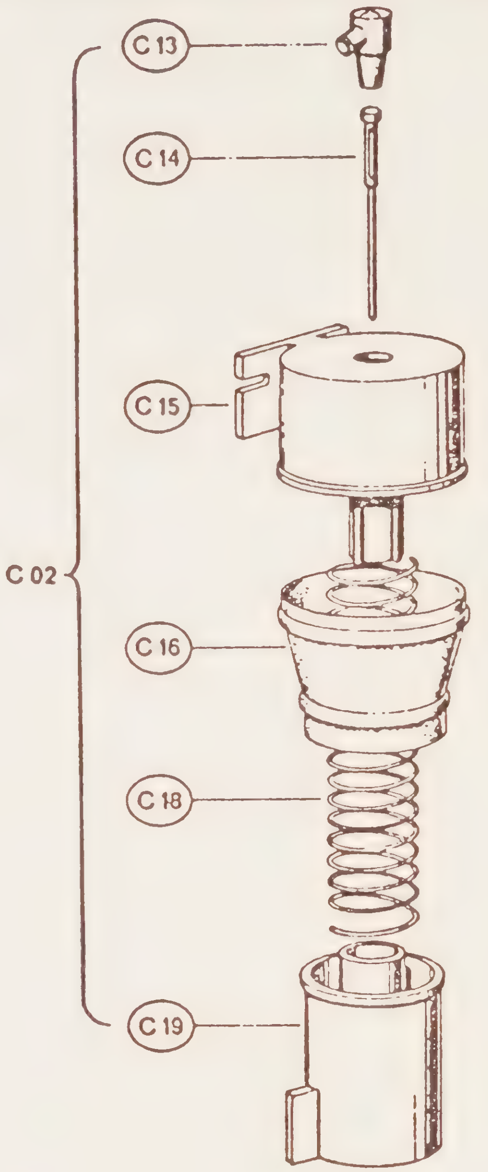


Fig. 1.16 MANIFOLD ASSEMBLY

Part No.	Req'd	Part name
B11	1	Cap
B12	1	Piston
B13	1	Check valve body
B14	1	Elbow
B15	3	Hose 7/12 x 25 mm
B16	1	Hose 10/14 x 30 mm
B17	1	Lead weight
B18	1	Piston
B19	1	Rubber collar
B20	1	Vacuum valve body
B21	1	Vacuum valve arm assembly
B22	1	Air inlet valve arm
B23	1	Rubber seal
B24	1	Air inlet valve body
B25	1	Hose 7/12 x 85 mm
B26	1	Hose 7/12 x 250 mm
B27	1	Hose 7/12 x 250 mm
B28	1	Hose 7/12 x 370 mm
B01		Manifold assembly parts No's B11 through B24 incl.
B02		Check valve assembly
B03		Vacuum valve assembly
B04		Air inlet valve assembly



Water Timer



Discharge Timer

Part No.	Req'd	Part name
C11	1	Water timer, jet holder
C12	1	Water timer, jet
C13	1	Discharge timer, jet holder
C14	1	Discharge timer, jet
C15	2	Upper body
C16	2	Rubber sleeve
C17	1	Spring, length 430 mm
C18	1	Spring, length 360 mm
C19	2	Lower body
C01		Water timer assembly
C02		Discharge timer assembly

Fig. 1.17 TIMER ASSEMBLIES

Part No.	Req'd	Part name
D11	1	Upper lifter body
D12	1	Spring, length 230 mm
D13	1	Rubber sleeve
D14	1	Lower lifter body
D15	2	Stud
D16	1	Rubber diaphragm
D17	1	Valve body
D18	1	Copper wire
D19	1	Connecting rubber sleeve
D20	4	Screw
D21	2	Arm
D01		Discharge valve assembly parts D11 through D21 incl.

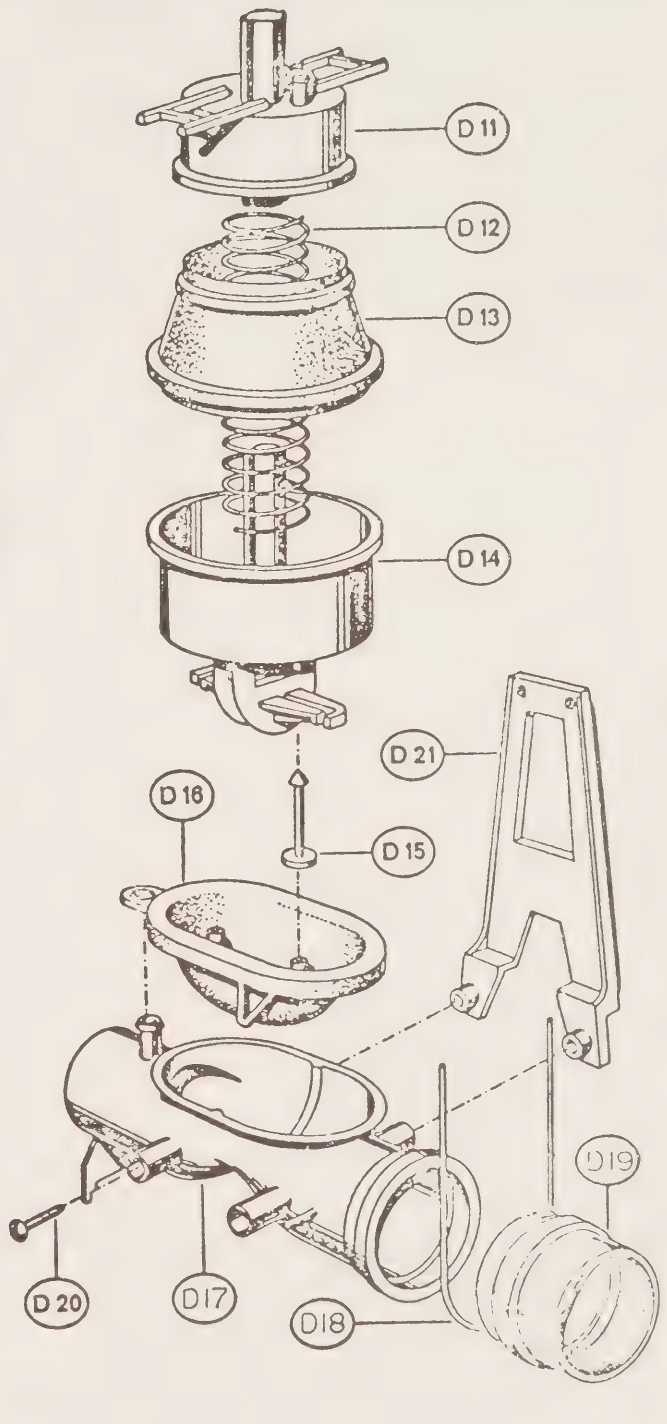
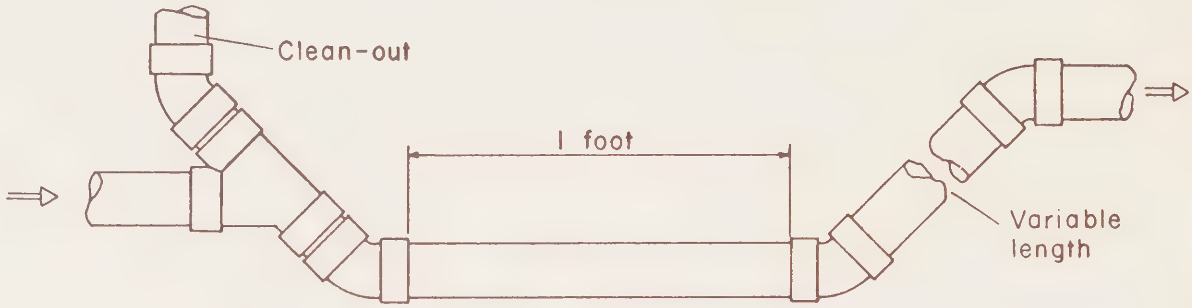


Fig. 1.18 DISCHARGE VALVE

a) FABRICATED FROM SOLVENT-WELDED FITTINGS



b) FABRICATED FROM CURVED PIPE LENGTHS

(Connected to main by rubber ring joints.)

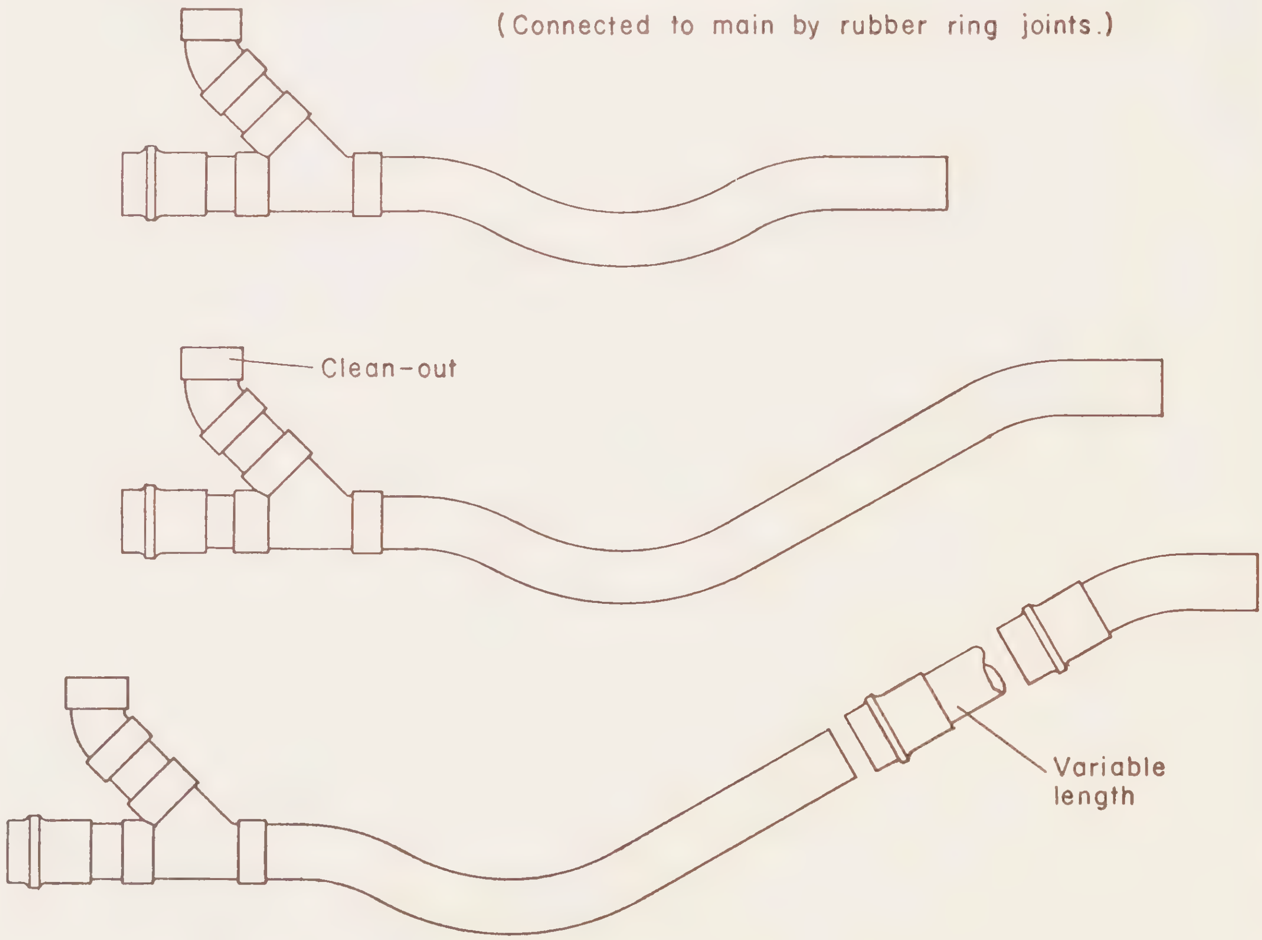


Fig. 1.19 BLACK WATER SYSTEM TRANSPORT POCKETS

Transport pockets are essential to the operation of vacuum sewers and they are shallow traps in a vacuum main, used for re-forming liquid plugs. Between transport pockets the pipe is sloped to ensure that when the liquid plugs break down, the wastewater flows by gravity into the pockets and collects to form new plugs. Pockets vary in size and shape depending on the quantity of wastewater to be carried in the mains and on the pipe profile used for a particular application.

The transport pockets used in the black water system are illustrated in Figure 1.19. In grey water and one-pipe systems, they consist of low points in the mains created by using specially-designed pipe profiles.

The pipe profiles used for black water mains are shown in Figures 1.20, 1.21, and 1.22. To ensure system reliability, the spacing of the pockets, and the rise between them, have been determined empirically. A pocket is required before every vertical or up-grade section of pipe. AB Electrolux has set the maximum vertical distance between pockets as five feet (1.5 metres) and the total rise in any stretch of pipe as 16½ feet (five metres).

The pipe profile recommended for the one-pipe system (Fig. 1.23) is formed by laying the mains in a wave pattern (ref. 4). Down-grade sections of pipe may be straight and without pockets, only if they empty directly into the vacuum collection tank. Where down-grade sections of pipe are followed by one or more lift sections, the down-grade section should contain transport pockets at recommended intervals. In the wave-form profile the difference in elevation between the crests and troughs of the wave is a minimum of 1.5 pipe diameters and the distance between adjacent troughs is 150 to 180 feet (50 to 60 metres). The troughs, of course act as transport pockets. As in the black water systems, the maximum total lift between any two points is 16½ feet (5 metres).[6]

The pipe profiles used with the grey water system are shown in Figure 1.24 (ref. 7). To prevent overloads, the grey water mains are laid in crested waves so that it is necessary to move each plug only a short distance over each wave crest during each transport period. If required, gravity flow will perform most of the transport in the sloped sections of pipe; therefore, this profile is preferable to the undulating wave form.[7]

AB Electrolux states that the grey water mains and common service laterals must not be laid up-grade. Up-grade transport is possible in single service laterals (serving one house) and should be accomplished as close as possible to the grey water valve.[8]

Certain design details must be followed to ensure the proper operation of vacuum sewers. The primary requirements are as follows:

1. Only long radius 45 degree and 90 degree bends should be used.
2. In black water systems, all branch pipe, house service, or similar types of connections should be made with a 45 degree Y-branch and a 45 degree elbow, both having the size of the larger pipe being connected, and the centre line of the incoming line must be at least one-half pipe diameter higher than the centre of the main pipe. As the transport velocities in grey water and one-pipe systems are lower than in black water systems, 90 degree connections are permitted but the fittings must still equal the size of the larger pipe being connected.
3. Any branch pipe, house service, etc., having a negative slope (i.e. sloping up in the direction of transport) must include a check valve immediately before the connection to a main to prevent backflow into the branch pipe.
4. Clean-outs are required at each transport pocket and at each end of every vacuum main; in service laterals at the point of connection to the main; in buildings at the end of each branch pipe, at the top of each stack, at every third floor in each stack and every 66 feet (20 metres) on horizontal pipes.
5. Vacuum pipe must be securely anchored at all changes of direction, at the remote end of branch pipes and house connections, and on both sides of fittings. Where pipes are run horizontally in walls or floors the pipes must be clamped every three feet (one metre) and in vertical stacks clamps must be placed every five feet (1.5 metres). The clamps consist of a metal strap with a shock-absorbing non-abrasive rubber insert.

[6]The maximum lift between pockets was not stated in the reference material available, except that the total lift is to consist of a series of "minor lifts" (ref. 4).

[7]The sources of information used for this section (ref. 4, 7) are drafts of proposed technical manuals. It may be assumed that, in the final versions, the crested wave form will be used for both grey water mains and one-pipe system mains.

[8]This statement appears to be somewhat inconsistent when compared to the descriptions of the black water and one-pipe systems. Presumably the grey water mains would have some lift capacity.

6. Vacuum pipes must be designed with appropriate provision for normal expansion and contraction due to temperature changes. This can be accomplished by using flectural offets, bends, or loops. If rubber joint connections are used, the joints will take up the changes of length of the pipes.
7. Where mains are laid in wave-form, connections to them should be located in the gravity-flow part of the main immediately downstream of a wave crest.
8. Isolating valves may be included at strategic locations in mains to facilitate inspection and maintenance work.

Indoor clean-outs consist simply of a 45 degree Y-branch, a short length of pipe, and a rubber plug (Fig. 1.25b). Outdoor clean-outs (Fig. 1.25a) require a sufficient length of vertical pipe to reach an elevation close to the ground surface. A recent innovation in outdoor clean-out design consists of the inclusion of a length of flexible hose in the clean-out pipe immediately above the connection to the main. This flexible section prevents damage caused by frost heave or other soil disturbances near the clean-out and allows it to be installed vertically, regardless of any slope in the main at the point of connection.

The length of vacuum mains and the maximum number of units which may be served are determined by the available pressure differential and the amount of headloss generated by the pipe network. Each case should be studied individually since vertical and horizontal distances will be determined by physical constraints in each installation. In general, as an indication of the capabilities of vacuum transport, the following limits may be assumed to apply to all vacuum systems:[9]

— maximum length per main = 6,000 ft. (2,000 m. approx.)
— maximum lift in one continuous length of pipe = 16½ ft. (5 m. approx.)
— maximum number of houses per main = 100 (This number is preferable for reliability of service but may be increased at least threefold without exceeding the physical capacity of the system.)

1.4.3. *Collection Tanks:*

The collection tanks receive wastewater (black, grey, or combined sewage) transported by the vacuum mains and store it until it is removed for treatment or disposal. They are designed to withstand an outside pressure of one atmosphere over and above other structural requirements. They are cylindrical with convex ends, and may be installed either horizontally or vertically. To prevent sludge accumulation, horizontal tanks may be installed with a slight slope toward the sludge removal point. Vertical tanks are usually equipped with conical bottoms sloping to sludge removal pipes. The material used is either steel (welded) or fibre glass. To retard corrosion, an epoxy paint coating is required inside the steel tanks and the outside surface may be coated in accordance with local conditions. They may be located above ground, or underground, with precautions taken to prevent floating in case of a high groundwater table. Underground tanks are usually preferable because of the lower lift required and this is particularly important in grey water and one-pipe systems which carry greater volumes of wastewater than black water systems. Protection against freezing may be provided by locating tanks in a heated, above-ground building or basement. Where it is preferable to use underground tanks these units may be placed so that they are at least partially below the frost line with any surfaces above it protected by insulating material.

Each is equipped with at least one access hatch, and on the top of the tank is a connection for a vacuum draw-off line, a vacuum relief valve (air inlet valve) and one-half inch nipples for electric cables which are attached to level control and alarm sensors. A method of emptying it is also provided and this is achieved in a number of ways, depending on the type of system used; for example, holding tanks employ either a three-inch diameter standpipe or a valved discharge pipe at the bottom, both of which may be fitted with quick-release couplings for scavenger truck hoses. Collection tanks which discharge intermittently to either gravity sewers or to treatment systems may be emptied by means of discharge pumps located outside the tanks, or they may be of a submersible type and located inside. Collection tanks also may serve as separation tanks for black water, in which case sludge may be drawn off through valves at the bottom and the supernatant may be pumped off through discharge lines at some height above sludge zone.

[9] The available information concerning the recommended maximum length and lift of vacuum mains appears to be contradictory and incomplete. The values listed above are suggested limits only; the capacity of each installation must be determined individually.

To ensure the reliability of the vacuum systems, all but the smallest installations should include two collection tanks and twin discharge systems, each with sufficient capacity to carry 100 per cent of the design load.
Collection tanks may be fitted with float-type or electrode-type level sensors to perform the following functions:

1. upper sensor — block switch to turn off the vacuum pumps if the tank becomes nearly filled;
2. second sensor — high level alarm switch for visual and/or audible alarm;
3. third sensor — to start discharge pump; and
4. fourth sensor — to stop discharge pump.

1.4.4 *Vacuum Reserve Tank:*
A vacuum reserve tank may be installed between the collection tanks and the vacuum pumps. Its purpose is to receive the air which enters the system to reduce the frequency of vacuum pump off-on cycles. Vacuum reserve tanks are similar to collection tanks in construction although they need no pump-out equipment or level sensors.
Vacuum reserve tanks are not included in many installations since the collection tanks can be designed so that they will be only partially filled with wastewater, with about half of the tank volume acting as a vacuum reserve. The decision to use a separate vacuum reserve tank, in preference to a vacuum reserve volume in the collection tanks, depends primarily on the availability and cost of tanks of various sizes and on the collection station's space requirements.

1.4.5 *Vacuum Pumps:*
The vacuum pumps used in all but the smallest installations should be of the liquid ring type with cast iron impellers and pump housings. The pumps are controlled by vacuum switches which operate them intermittenly, maintaining the vacuum in the system between pre-selected high and low limits (usually 0.6 to 0.7 atmospheres in the collection tanks). A check valve is included between each vacuum pump and the vacuum reserve or collection tank to prevent air from entering the system when the pump is not operating.
The service liquid used with the liquid ring vacuum pumps may be water or oil. Where water is used a glycol-base antifreeze and a corrosion inhibitor are advisable. The service liquid tank should be corrosion-resistant and airtight. The tank is vented, by a plastic pipe of diameter not less than the vacuum line, to a point outside the collection station building and at an elevation above roof level and away from windows, doors, etc. Where possible, the service liquid tank may be isolated from pumps and electrical controls, as the corrosive fumes drawn from black water tanks by the vacuum pumps are discharged into the service liquid tank.

In smaller installations, including individual houses, railway cars, boats, etc., the vacuum pumps used are of the dry plate type. To remove offensive odours, these smaller systems are usually fitted with one or more carbon filters on the vent stack.
Vacuum pumps are usually powered by electric motors. In areas where frequent interruptions of electric service are expected, the vacuum collection station should include an auxiliary generator or alternate means of powering the pumps.
In small installations, such as single-family dwelling units, one vacuum pump may be used to service the vacuum system. Larger installations, which include office buildings, hotels and small groups of houses, require two vacuum pumps, each sized to accommodate the maximum flow. In these installations one pump is used as the duty pump with the second acting as a stand-by unit. In large installations, where several vacuum pumps are used, it is not necessary to include a 100 per cent stand-by capacity as one or two pumps may be removed from service without causing serious overloading to the others.

1.4.6 *Discharge Pumps:*
Discharge pumps are used to pump the collected wastewater to a treatment system or to conventional sewers. Centrifugal non-clog sewage pumps may be installed outside the tanks, or alternatively, submersible sewage pumps may be placed inside the collection tanks. The vacuum in the collection tanks may be relieved prior to discharge pumping; however, it is more convenient to choose pumps with a suction head sufficient to draw against the vacuum in the tank so that discharge may occur automatically at any time without interrupting the function of the system. Discharge pumps, and discharge lines, are usually installed in duplicate with each pump sized to accommodate the maximum load. A shut-off valve is mounted between externally located pumps and the collecting tank and the pumps must be installed to ensure that there is always liquid present in the pump housings to keep the pumps primed. Two check valves should be installed on the pressure side of both externally and internally mounted pumps. Where only one check valve is used, solid matter may jam the valve open causing air leakage into the system.
As an alternative to pumping, discharge of the collected wastewater may be achieved by air pressure. In this case, the collection tank must be designed so that it can be isolated from the rest of the system and pressurized.

1.4.7 *Wastewater Admittance Valves:*
A wastewater admittance valve is a device which acts as the interface between gravity pipes and vacuum pipes. It admits wastewater (collected by gravity) into the vacuum sewer system. Several types of wastewater valves have been used for different purposes and both Electrolux and Airvac are currently developing further varieties.

Grey water is usually transported within buildings by conventional gravity plumbing and the transfer of this wastewater from the gravity system to a vacuum system must be through a grey water valve. The grey water float valve (Fig. 1.26) is the unit originally designed as the interface between gravity and vacuum pipes in the grey water system[10] and it is a simple device consisting of a cylindrical plastic float within a cylindrical plastic chamber. The float chamber has an influent port (gravity side) located in the chamber wall and an effluent port (vacuum side) centrally located in the bottom of the chamber. The float is fitted with a rubber plug which seals the effluent port when the water level in the chamber is low. Because of its buoyancy, the float rises when sufficient water has entered the influent port, and the water is drawn through the effluent port by combined gravitational and pressure forces. The valve chamber is fitted with a cover, secured by screws, which prevents the float from rising out of the chamber but which will not prevent leakage in the event that it fails to open the effluent port.

In some installations it is necessary, within buildings, to transport grey water by vacuum. A wastewater admittance valve, or grey water valve, then must be installed near each fixture or group of fixtures to be serviced. The unit originally designed for this purpose is the Electrolux (Sanivac) two-inch piston-type valve, which operates automatically and is activated by water pressure on the up-stream side of the valve. The Sanivac piston-type valve (Fig. 1.27) is made of rigid PVC and consists of an inclined piston covered by a rubber sleeve which is clamped between the cover and the valve body. The activator mechanism (control valve) consists of a three-way valve with a rubber membrane which is sensitive to static pressure. Wastewater collects in the gravity line upstream of the grey water valve and, when a certain pressure is created, the activator mechanism opens a passage between the vacuum pipe and the valve cover. Air is drawn out of the valve and the piston is lifted, compressing the stainless steel spring. Wastewater is then pushed into the vacuum pipe by atmospheric pressure. When the static pressure on the activator mechanism decreases beyond a certain value, the connection between the vacuum pipe and the grey water valve is closed, preventing the increased downstream pressure from affecting the vacuum in the valve cover. When the upstream pressure decreases further, the activator mechanism admits air into the cover of the piston valve and the valve closes.

The advent of the one-pipe system for conventional plumbing systems created the need for a three-inch valve capable of transferring raw combined wastewater from a gravity pipe or a buffer tank to a vacuum main. Two such valves are now available: the Electrolux (Sanivac) three-inch valve and the Airvac valve. They may be used as alternatives to the float valve or two-inch piston-type valve for admitting grey water into vacuum pipes, in addition to their intended function of handling wastewater containing large pieces of solid material.

The three-inch Sanivac valve is a scaled-up version of the three-inch piston-type valve described above. Its original design allowed it to function in exactly the same way. Unfortunately, Sanivac piston-type valves tended to close before all the water had entered the vacuum main and before a sufficient quantity of air had entered behind the water to ensure efficient transport. The air volume admitted was about 25 per cent to 30 per cent of the liquid volume at NTP (ref. 30). Occasionally, the valve piston closed on solid objects in the wastewater and was prevented from sealing properly; consequently, the valve leaked air and water slowly into the main and had to be cycled manually to clear the obstruction.

The Airvac valve, developed by the Airvac division of the National Homes Construction Corporation as an alternative to the Sanivac valve, is also a piston-type vacuum-operated three-inch valve (Fig. 1.28). Unlike the original Sanivac valve, it is timed to remain open for a pre-selected period. The control mechanism consists of a sensor-timer unit and a three-way valve and it establishes both a minimum operating vacuum and the length of time during which the valve remains open. If there is sufficient vacuum available downstream of the valve, static pressure upstream (gravity side) causes the sensor-timer to open a passage in the three-way valve between the vacuum main and the vacuum valve. The valve piston then will be raised allowing the wastewater to be pushed into the vacuum main by atmospheric pressure. The sensor-timer is usually adjusted so that approximately equal volumes of air and water (at NTP) enter the vacuum system. At the end of a pre-selected period atmospheric air is allowed to enter the upper body of the vacuum valve and the valve closes.

The minimum vacuum required to operate the Airvac valve is temperature dependent and varies from 0.10 atmosphere at 10°F to 0.17 atmosphere at 135°F. The establishment of a minimum operating vacuum ensures that when a valve opens there will be sufficient pressure differential to create an acceptable transport velocity. Once the piston has been raised, increasing downstream pressure cannot cause the valve to close as there is a check valve between the vacuum pipe and the three-way valve.

The Airvac valve was designed with a timer when tests performed on the original Sanivac three-inch valve indicated that its operation was not completely satisfactory (ref. 30). As previously stated, non-timed valves do not admit sufficient air into the system and they tend to close on solid material in the wastewater. In addition, because untimed valves

[10]This unit has been used only in vacuum sewer installations in the Bahamas.

tend to close on the wastewater stream, a water hammer effect may be created upstream of the valve. Increasing upstream pressure then tends to open the valve momentarily and consequently the valve piston may cycle rapidly or fluctuate under certain operating conditions. A timed valve will close on the wastewater only when its operation has been delayed by the lack of sufficient vacuum long enough for a large volume of wastewater to collect upstream in the gravity piping or buffer tank.

Recently, Electrolux introduced a timer unit which may be used with the two-inch and three-inch Sanivac valves. The timer is combined with a vacuum wastewater valve, an activator mechanism, and a flap-type check valve to make an automatic timer-controlled valve unit (Fig. 1.29). The timer consists of several parts used in the vacuum toilet flushing mechanism, including the starter valve, discharge timer, and manifold assembly.

When a pre-determined static pressure is created on the gravity side of the wastewater valve, the activator mechanism opens a vacuum line from the main to the timer mechanism. The stem of the starter valve is held down by the timer's lower body in its at-rest position, so that a passage is open through the starter to the top of the timer. Air is drawn out of the timer, thereby lifting its lower body and releasing the starter. As in the vacuum toilet, the starter stem remains in its lower position unless there is a certain minimum vacuum available in the system. The operating cycle is then basically identical to a vacuum toilet. First, the timer opens the manifold vacuum valve which supplies vacuum to open the wastewater valve. It then opens the air inlet valve to close the wastewater valve, and finally rests on the starter, depressing the stem in preparation for the next cycle. The check valve is included to prevent pressure backlashes in the main from reaching, and possibly damaging, the wastewater valve.

Another recent development in the one-pipe system is the Electrolux transfer unit (Fig. 1.30), which consists of a piston-type wastewater admittance valve and an activator mechanism mounted inside a specially-designed fibre glass tank. This unit has been designed to act as the interface between the gravity and vacuum pipes in one-pipe systems, including conventional plumbing. Its primary function is to buffer the widely variable incoming flows and admit controlled volumes of wastewater into the vacuum mains. In this way, the peaking characteristics of the flow in the mains can be controlled, permitting the use of small pipe sizes and adequate transport velocities.

The activator mechanism is sensitive to static pressure and is adjusted to open the admittance valve at a maximum water level and to close it at a minimum level. Wastewater enters the vacuum system through a float which is connected to the piston-type admittance valve by means of a flexible hose. Air does not enter the vacuum main as a slug following the liquid, as is customary in vacuum systems employing timed wastewater admittance valves. An air inlet nipple, located on the float above the water level, allows air at atmospheric pressure to continuously enter the vacuum system, provided the admittance valve is open. The air becomes entrained within the incoming wastewater and later separates from it in the vacuum mains.

Although the transfer unit may appear unnecessarily complex it has one advantage over the timed piston-type wastewater valves. Valves timed to remain open for a pre-selected period admit the correct air-to-water ratio only if there is the correct amount of water collected upstream of the valve. With the transfer unit, the air-to-water ratio is a function only of the size of the air inlet nipple and will not be influenced by the liquid level in the buffer tank, provided the tank is not flooded sufficiently to submerge the float. Maintaining the correct air-to-water ratio is important for the establishment of a minimum transport velocity and for the separation of wastewater plugs in the vacuum mains. It is possible that, during peak loading periods, parts of certain mains may tend to become "waterlogged" if there is insufficient volume of air in the pipes. This can occur if excess volumes of wastewater collect upstream of lift sections until the resulting static head exceeds the available pressure differential.

As the transfer unit does not include a timer for the admittance valve, it apparently does not have a starter mechanism to establish a minimum operating vacuum and this deficiency may tend to offset the advantage gained by the establishment of a constant air-to-water ratio.

Airvac is also developing a combination buffer tank and wastewater admittance valve which is referred to as a "pot valve". This unit is based on a timed, three-inch Airvac valve.

Wastewater admittance valves probably will represent the most revised part of the vacuum sewer system. More changes can be expected as research and practical experience are applied to the search for the ideal valve: one that is simple, inexpensive, practically indestructible; and one which establishes a minimum operating vacuum and admits the correct air-to-water volume ratio under all conditions.

1.4.8 *Urinals:*

The wastewater from urinals also may be transported in vacuum pipes. Urinals of any make and design may be used if they are located so that the wastewater flows by gravity to the vacuum admittance valve. Elecrolux manufactures two types of urinal mechanisms. A manually controlled unit is provided with rinse water by a manually-opened self-closing flushing valve. An automatic unit includes a modified vacuum toilet flushing mechanism which controls the sequencing of rinse and discharge operations;

the cycle being initiated by a pressure-sensitive activator mechanism.
Urinals may be serviced by either piston-type or diaphragm-type vacuum wastewater valves. The piston valves with diaphragm-type activator mechanisms are used in installations which include automatic urinals, require lifts in the vacuum pipes, or produce relatively large quantities of wastewater. The diaphragm-type valve is the same as the unit used in the vacuum toilet; in this case, the valve is controlled by a specially-designed float-type activator. This valve and activator combination is used for small quantities of wastewater where no lift is required and also it may be used for other small fixtures, such as handbasins where the wastewater is free of solids.

1.4.9 *Air Admittance Valves:*
An air admittance valve assembly can be added to the upstream end of vacuum mains to admit a controlled volume of air to the main at pre-selected time intervals. As described previously, when a plug of wastewater breaks down the air pressure behind it is lost, and once re-formed, the plug cannot move until a pressure differential is restored by the entrance of air into the main somewhere upstream from it. To ensure that flow continues in the mains, controlled volumes of air may be periodically admitted by a timed valve at the upstream end of the mains. This may be an Airvac or Sanivac valve activated by a timed solenoid valve instead of by a pressure-sensitive activator mechanism.
Air admittance valves may be used to ensure that wastewater will not collect in the mains for extended periods, causing problems of solid build-up, septic conditions, or freezing. In cold climates, air admittance valves may prove essential as long retention periods could lead to heat loss from the wastewater. Existing vacuum sewer installations which use float-type grey water valves or non-timed piston-type valves and where insufficient amounts of air enter the mains, may be improved by the use of air admittance valves.
An air admittance valve assembly includes the vacuum-operated valve, a timer and solenoid valve for activation, a power source, and the necessary equipment housing. These valves will cause increased use of vacuum pumps and, where more than one valve is used, they should be synchronized to prevent overloads in the vacuum system.

1.5 Description of Collection Stations

Vacuum collection stations normally contain wastewater collection tanks, vacuum reserve tanks, vacuum pumps, and sewage pumps, plus the control equipment required for automatic operation. They may also serve as treatment plants where on-site treatment is used. The following paragraphs outline the layout and operation of various types of collection stations.

The simplest type of collection station is a black water collection station utilizing discharge by scavenger truck (Fig. 1.31). Black water from the vacuum toilets enters the collection tank (1) by means of the vacuum mains (2) which may be isolated from it by shut-off valves (3). Vacuum is maintained by a vacuum pump (4) which, when not in use, is isolated from the tank by a check valve (5). The vacuum switch (6), in conjunction with the electrical control panel (7), turns the vacuum pump on and off to maintain a desired range of pressure in the system. When the collection tank is about three-quarters full and is ready for emptying, a level sensor (8) transmits a signal to the control equipment which activates an alarm. If the tank continues to be filled and the liquid level reaches the second sensor (9), a signal is sent to the control panel and the vacuum pump starter is blocked to prevent the system from becoming overloaded. The wastewater is removed from the tank by a scavenger truck through a stand-pipe fitted with a quick-release coupling (10) which, in this case, passes through the access cover (11). Before the wastewater can be removed the vacuum pump is turned off, the mains are isolated from the collection tank, and air is admitted to the tank through the vacuum relief valve (12).
Larger black water collection stations and one-pipe collection stations are usually designed to discharge the collected wastewater to gravity sewers or directly to treatment plants without relieving the vacuum in the collection tanks. This type of collection station (Fig. 1.32) is similar to the station previously illustrated except that centrifugal sewage pumps (19) have been added. These pumps then necessitate the following additional equipment:

- (13) shut-off valve (normally open);
- (14) two check-valves;
- (15) small-bore pressure equalization line (required to keep the sewage pump primed);
- (16) solenoid-activated valve which closes when the pump is running to prevent the return of the sewage to the collection tank (Items 15 and 16 are not required for submersible pumps);
- (17) level sensor (plus associated control equipment) to turn on the discharge pump at the high level; and
- (18) level sensor (plus associated control equipment) to turn off the discharge pump at the low level.

The two-pipe system requires a collecting station with separate collecting tanks and methods of disposal for black and grey water. The two-pipe collecting station illustrated in Figure 1.33 also includes submersible sewage pumps, a vacuum reserve tank, and one of the possible arrangements of multiple vacuum pumps. The control equipment used for this type of station is similar to that illustrated in Figures 1.31 and 1.32.

Figure 1.34 illustrates a collecting station for a large one-pipe system. The collection tanks and discharge systems are duplicated and cross-connected so that service may be maintained while one collection tank or one discharge pump is out of service. Each discharge pump is sized to accommodate the design flow entering both tanks. If one discharge pump should cease functioning, the wastewater level in its tank would eventually reach the high level warning sensor which, in this case, would not only produce a warning signal but would automatically cross-connect the effluent lines of the two tanks, allowing both to be emptied by one pump. The malfunctioning pump may be isolated manually for repair at any convenient time. The influent lines to the collection tanks are provided with manually controlled cross-connections to permit isolation of either tank for cleaning.

Figure 1.34 also illustrates an alternative type of vacuum pump installation. Each collection tank has one pump sized to accommodate the design flow into that tank. A third pump, which has sufficient capacity to operate on either tank, is used as a stand-by unit. If one duty pump fails to produce the required maximum operating vacuum within a pre-selected period the stand-by pump is automatically started and connected to the appropriate tank.

1.6 Liljendahl Treatment Process

The Liljendahl treatment process was developed for use with the vacuum sewer system. Black water, which is produced in small quantities and in highly concentrated form, may be treated efficiently by a chemical process consisting essentially of massive lime dosage followed by ammonia stripping. Black water solids are allowed to settle in the collection tank and they are periodically pumped from there to a sludge holding tank; sludge may then be disposed of in any convenient manner. The black water supernatant is removed from the collection tank periodically in a fixed quantity and pumped to a lime reactor which is controlled automatically to add lime to the wastewater and to provide both mixing and sedimentation. High alkalinity (pH12) in the reactor causes the precipitation of phosphates, converts nitrogenous compounds to ammonia, and acts as a disinfectant. After sedimentation the lime sludge is automatically returned to the collection tank by vacuum from where it is transferred to the sludge holding tank with the rest of the solids. Where anaerobic digestion of the black water sludge is desirable the lime sludge from the reactor is not returned to the collection tank but is disposed of separately. The supernatant from the lime reactor flows to an ammonia stripping unit where it is aerated prior to disposal. Recarbonation of the effluent may be necessary to decrease the residual pH prior to disposal to a receiving body of water.

As an alternative to direct disposal of the black water plant effluent, the treated wastewater may be combined with raw grey water (Fig. 1.35). The residual alkalinity in the black water effluent will then precipitate the phosphorus in the grey water. The combined wastewater may be treated in any appropriate manner.

The Liljendahl sewage treatment system used on black water purportedly produces an effluent "disinfected from bacteria, viruses, and intestinal parasites" (ref. 15). In addition, the system is said to remove 95 per cent of the phosphorus and 90 per cent of the nitrogen from the black water. If grey water is also considered, the system produces a reduction in organic matter comparable with conventional treatment and a far greater removal of nitrogen and phosphorus.

The Liljendahl treatment process is certainly not the only efficient method of treatment available; in fact, its cost has limited it mostly to some early installations and to locations where pollution control regulations are very strict. Other methods (chemical, physical and biological) may prove useful in treating black water.

One-pipe systems using vacuum toilets produce a more highly concentrated wastewater than conventional gravity systems, and for this concentrated waste, modifications of currently-used biological processes may prove efficient.

PIPE DIAMETER (inches)	POCKET SPACING (A) (feet)	REQUIRED LIFT (H) (inches)
2	130	4
2·1/2	160	5
3	190	6

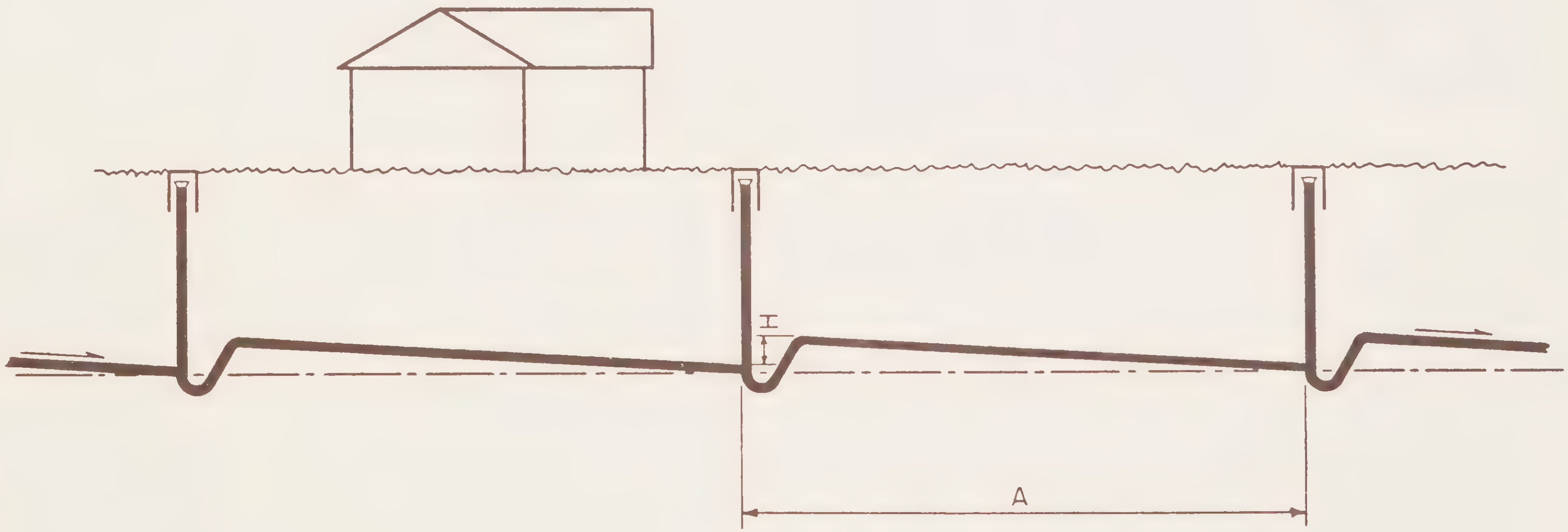


Fig. 1.20 BLACK WATER MAIN — HORIZONTAL TRANSPORT

PIPE DIAMETER (inches)	POCKET SPACING (A) (feet)
2	130
2·1/2	160
3	190

MAXIMUM LIFT

The lift (H) between any two pockets must not exceed 5 feet. The sum of all lifts $(H_1 + H_2 + \ldots H_n)$ must not exceed 16·1/2 feet.

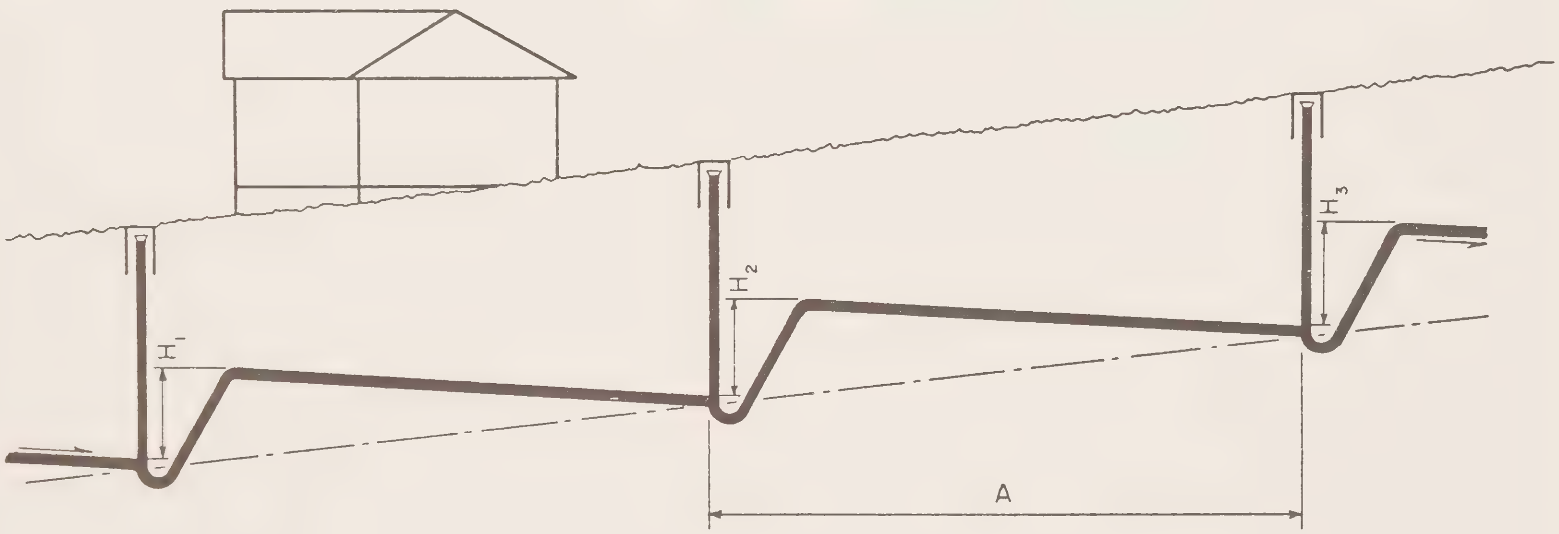


Fig. 1.21 BLACK WATER MAIN — UP-GRADE TRANSPORT

PIPE DIAMETER (inches)	POCKET SPACING (A) (feet)	REQUIRED FALL (H) (inches)
2	130	4
2·1/2	160	5
3	190	6

THIS PROFILE MAY BE USED WHERE THE SLOPE EXCEEDS 1/4 % FOR LESSER SLOPES THE PROFILE FOR HORIZONTAL TRANSPORT APPLIES.

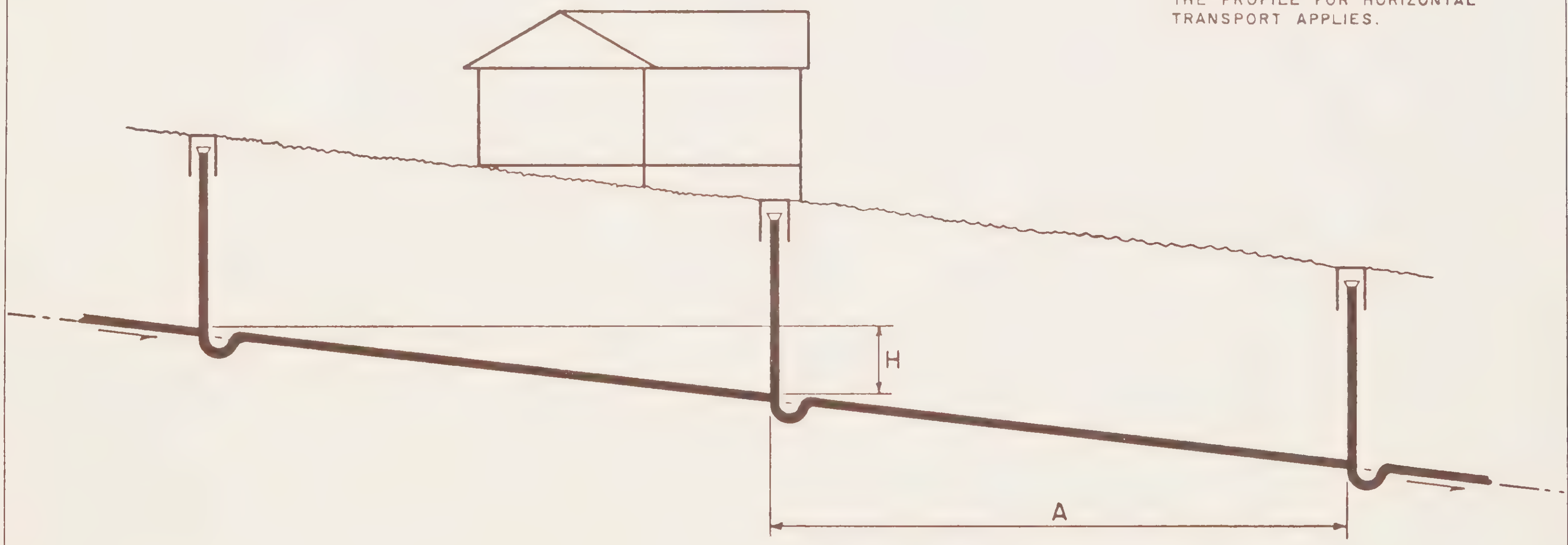


Fig. 1.22 BLACK WATER MAIN — DOWN-GRADE TRANSPORT

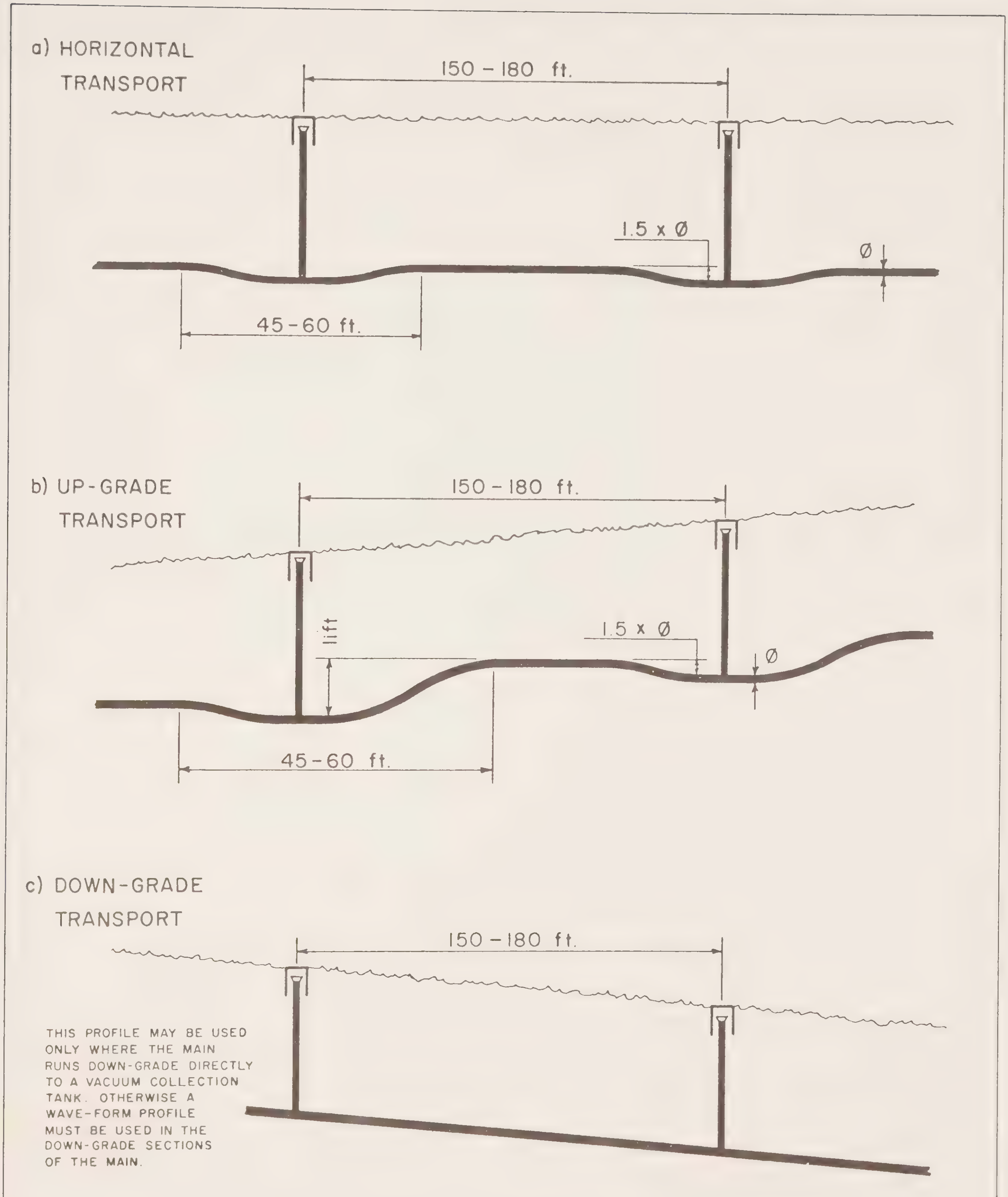
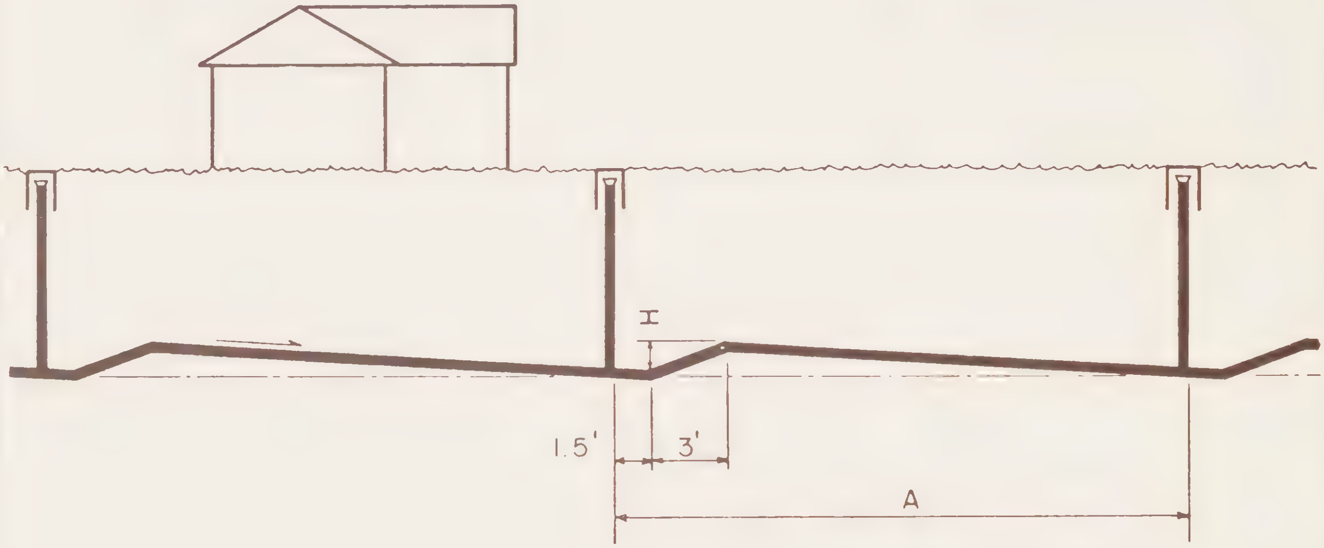


Fig. 1.23 ONE-PIPE VACUUM SEWER PROFILES

PIPE DIAMETER (inches)	POCKET SPACING (A) (feet)	REQUIRED LIFT OR FALL (H) (inches)
2	160	4
2-1/2	200	5
3	240	6



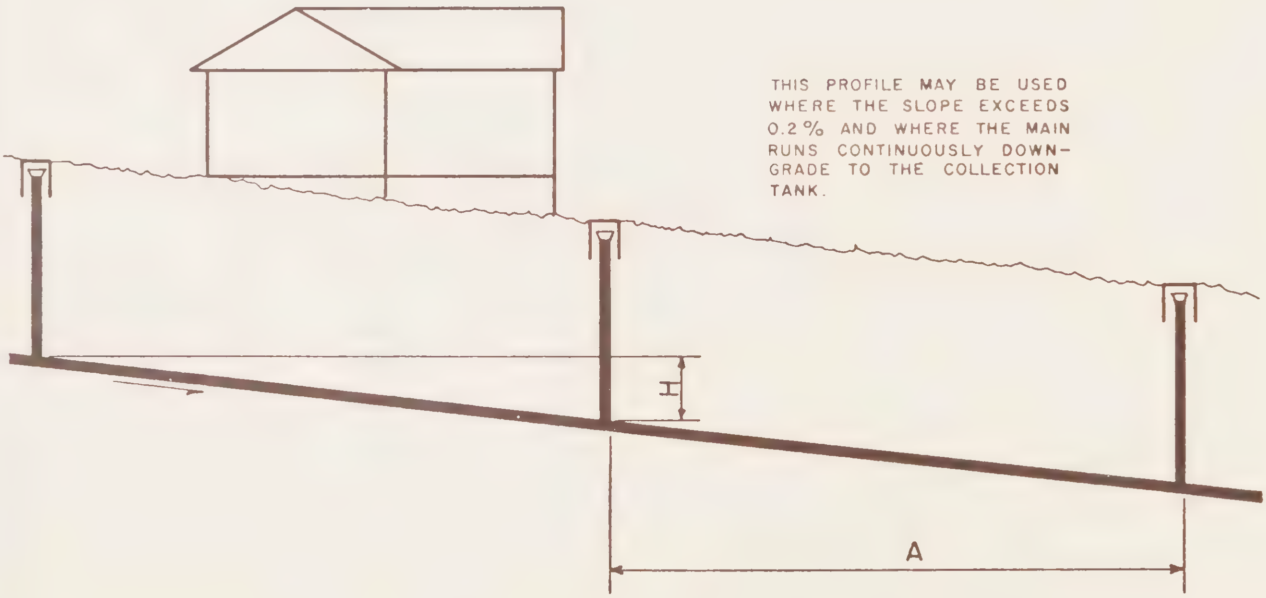


Fig. 1.24 GREY WATER VACUUM SEWER PROFILES

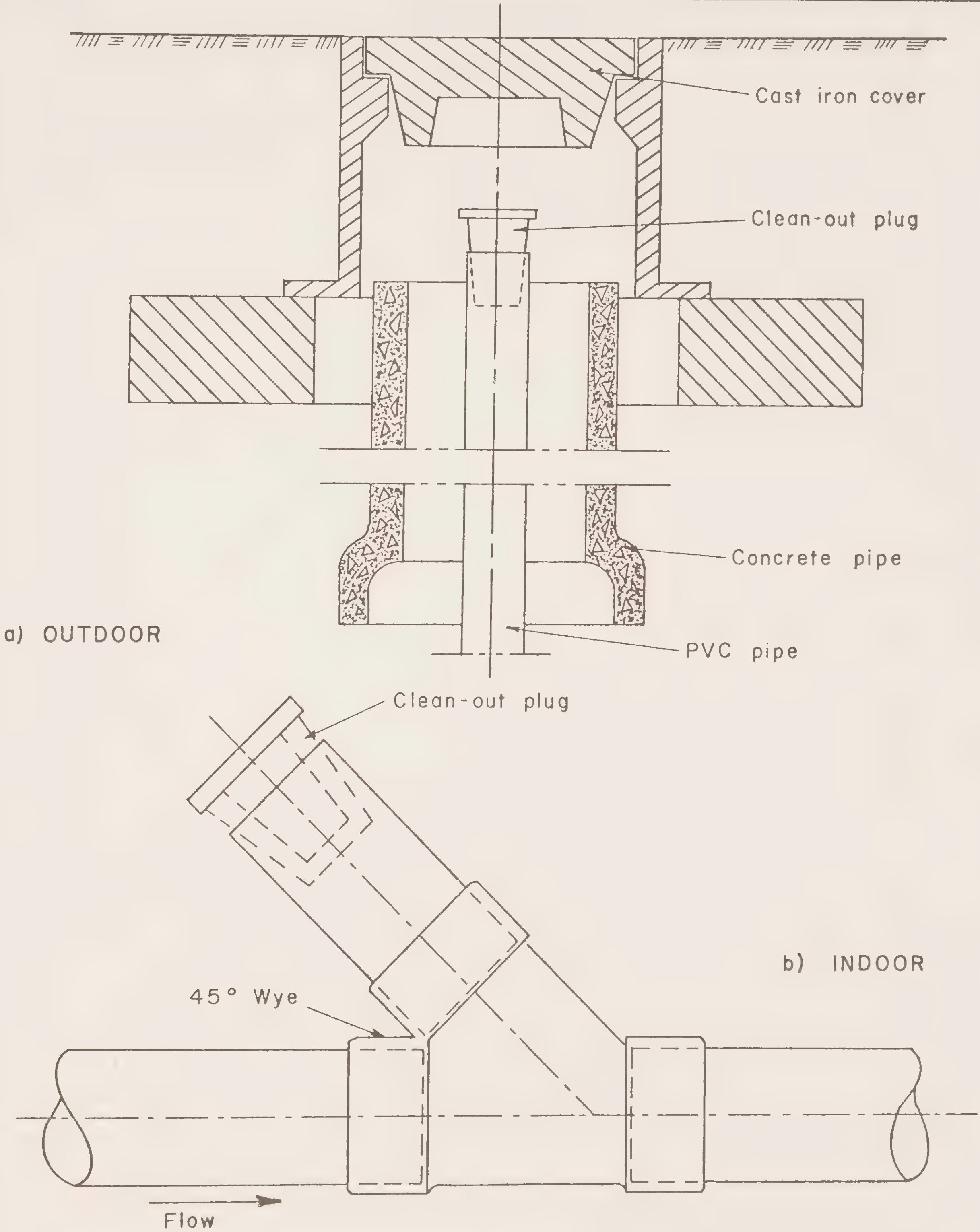


Fig. 1.25 CLEAN-OUTS

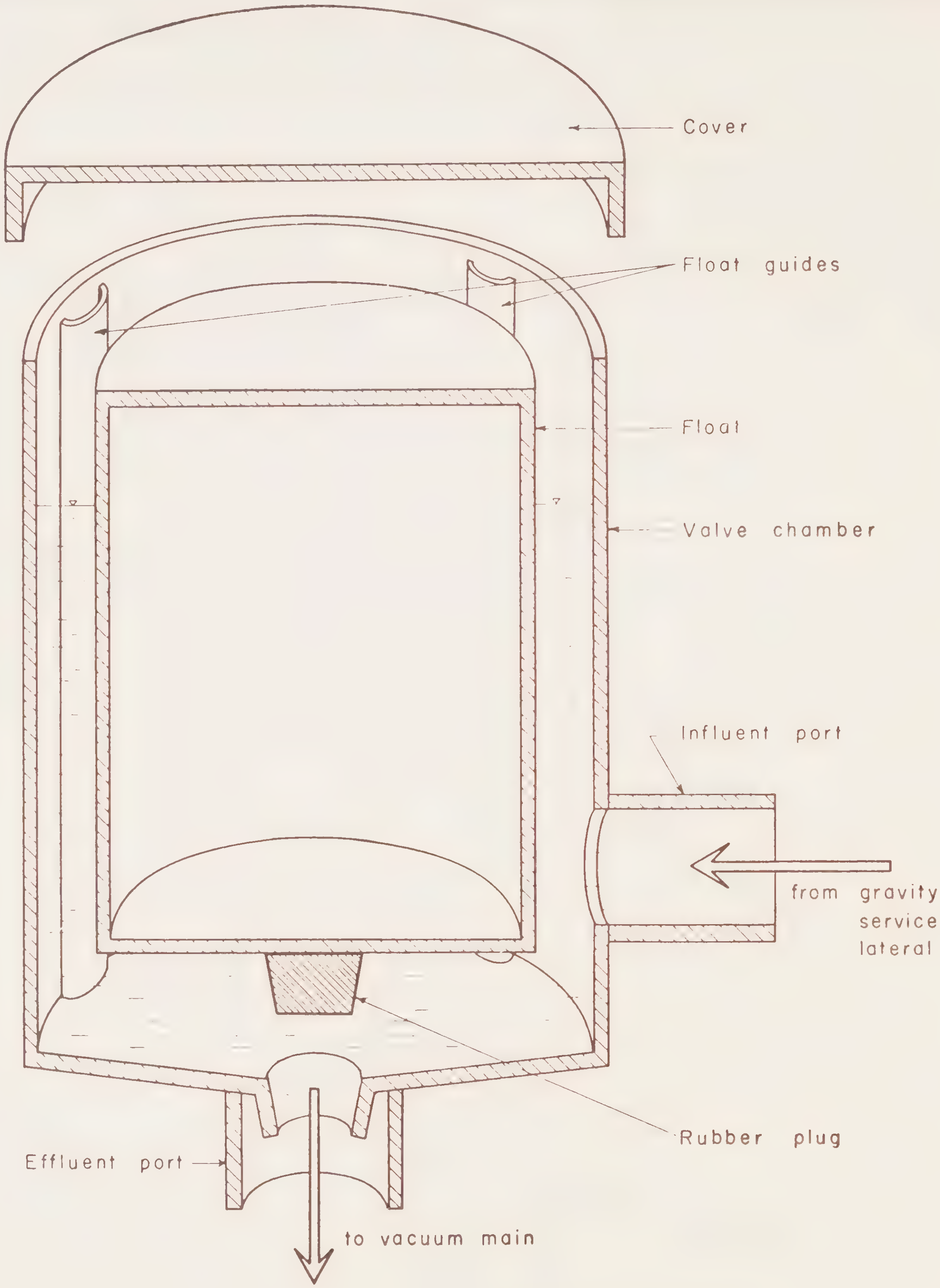
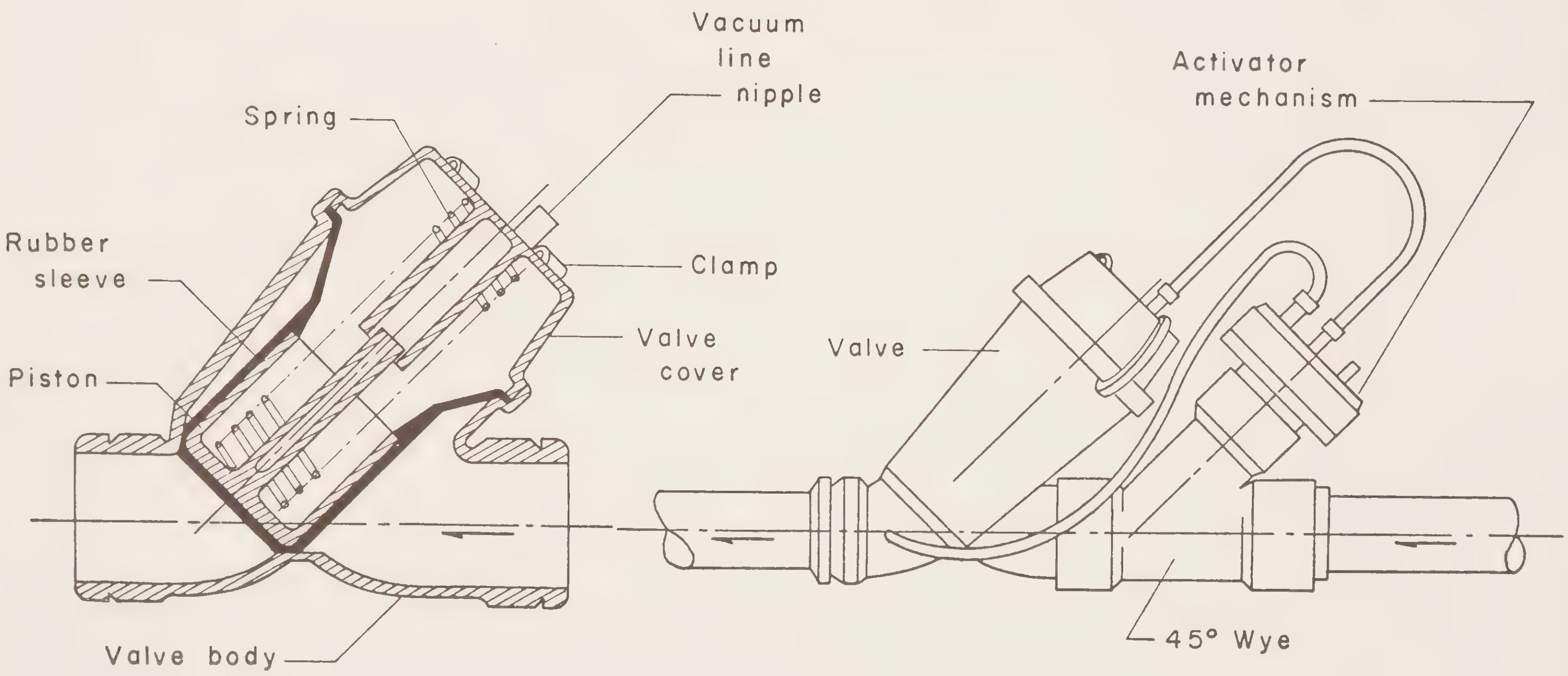


Fig. 1.26 GREY WATER FLOAT VALVE



a) CROSS-SECTION OF VALVE

b) VALVE WITH ACTIVATOR

Fig. 1.27 SANIVAC PISTON-TYPE VALVE

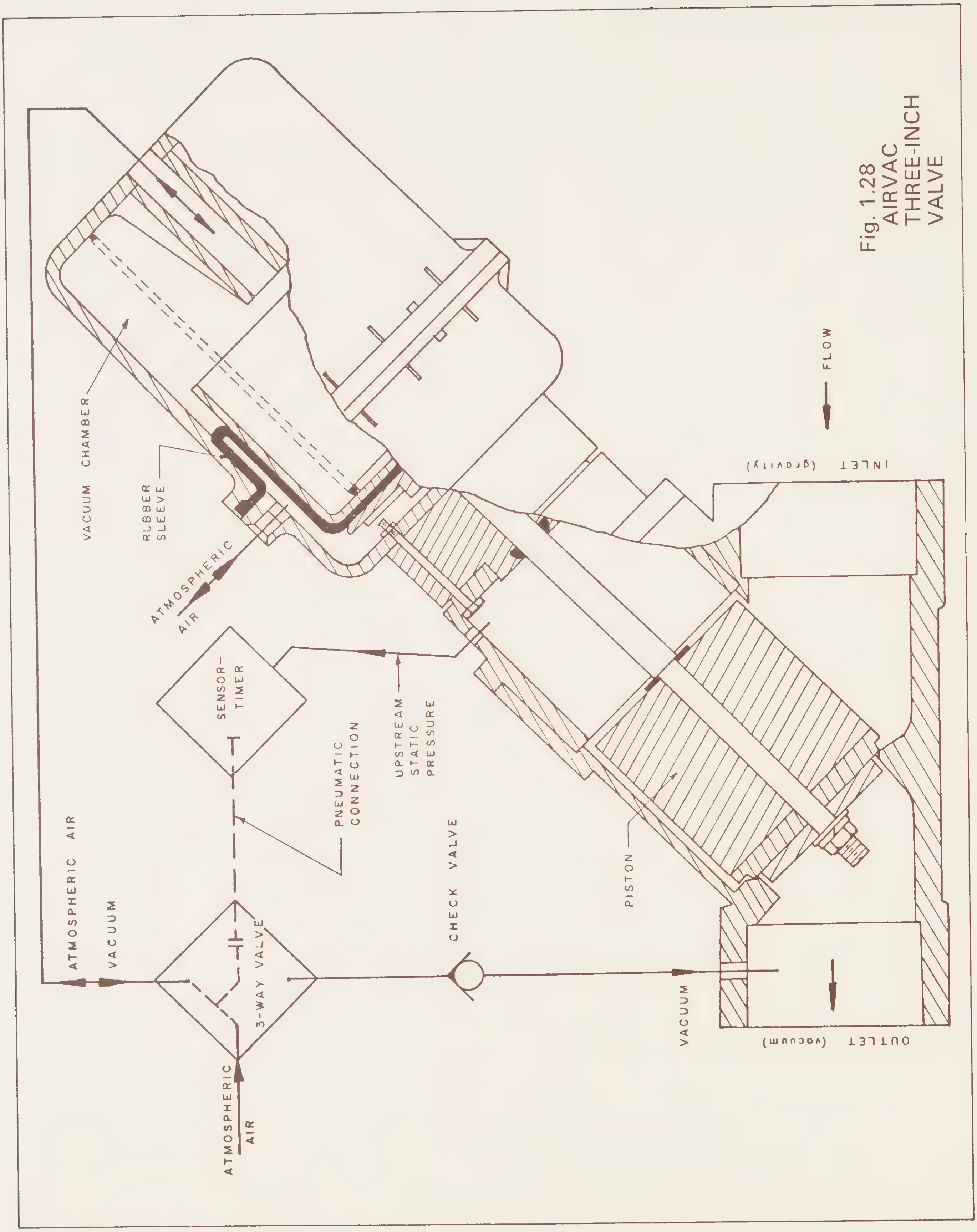


Fig. 1.28
AIRVAC
THREE-INCH
VALVE

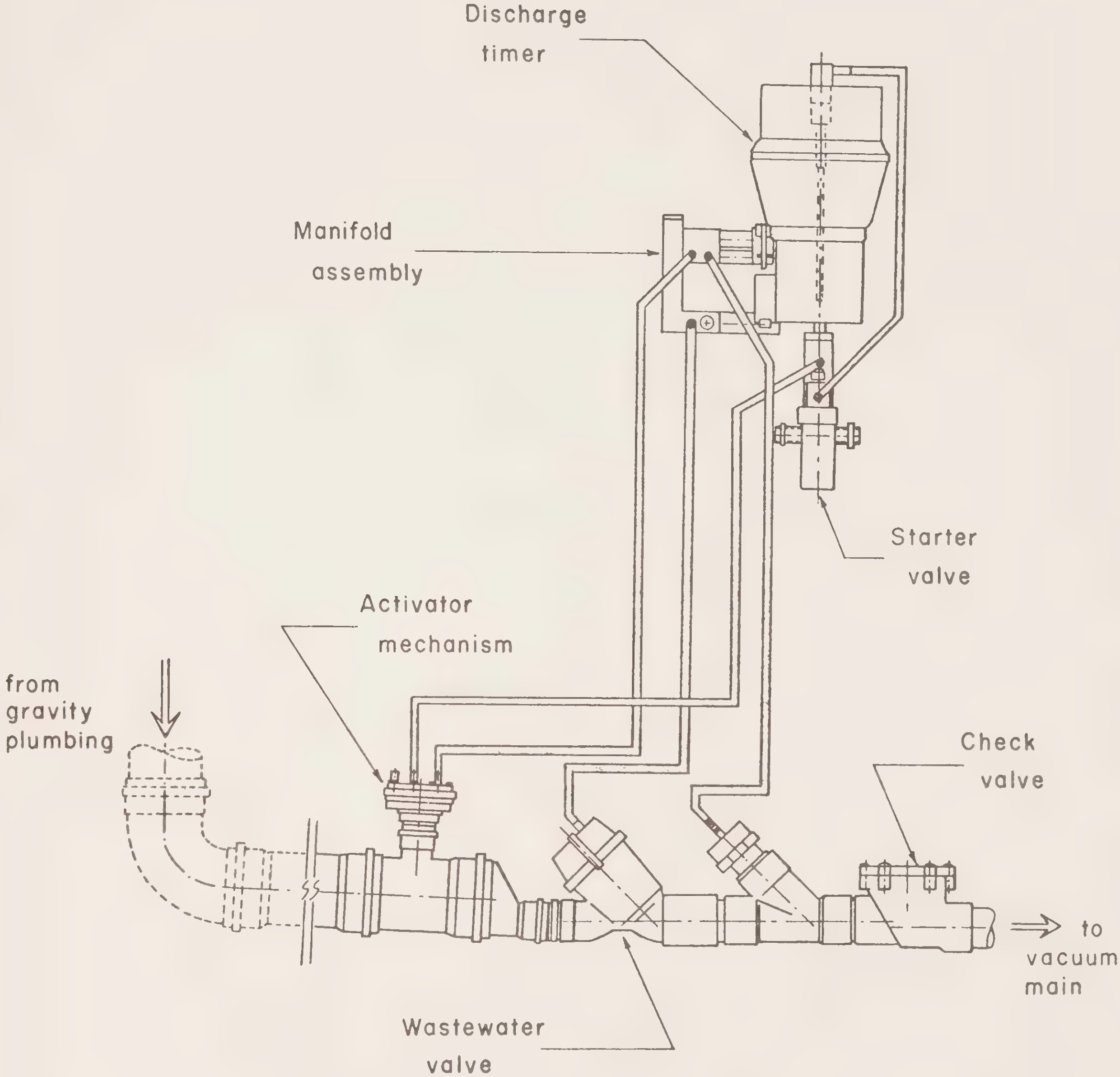


Fig. 1.29 TIMER-CONTROLLED SANIVAC VALVE

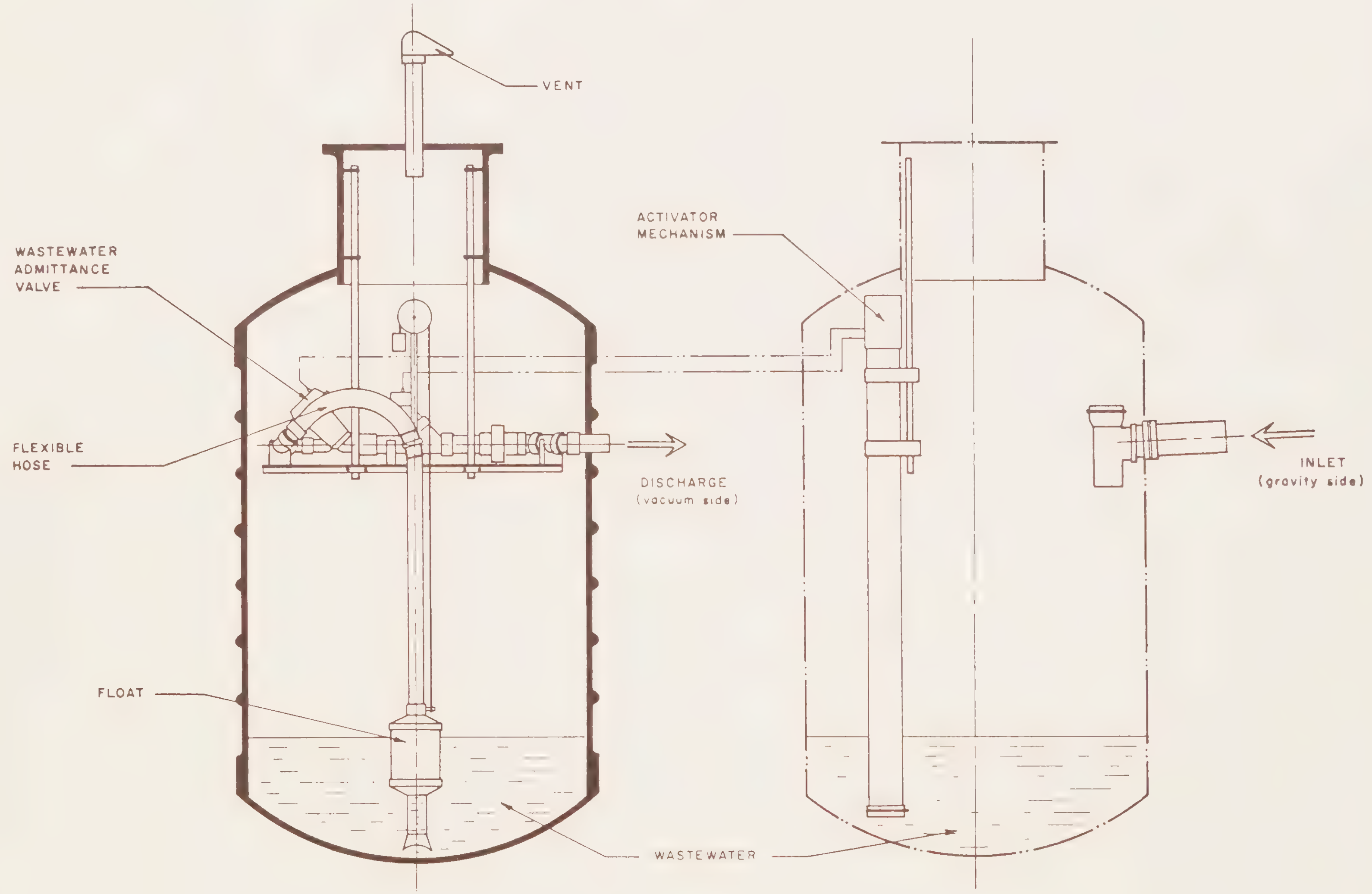
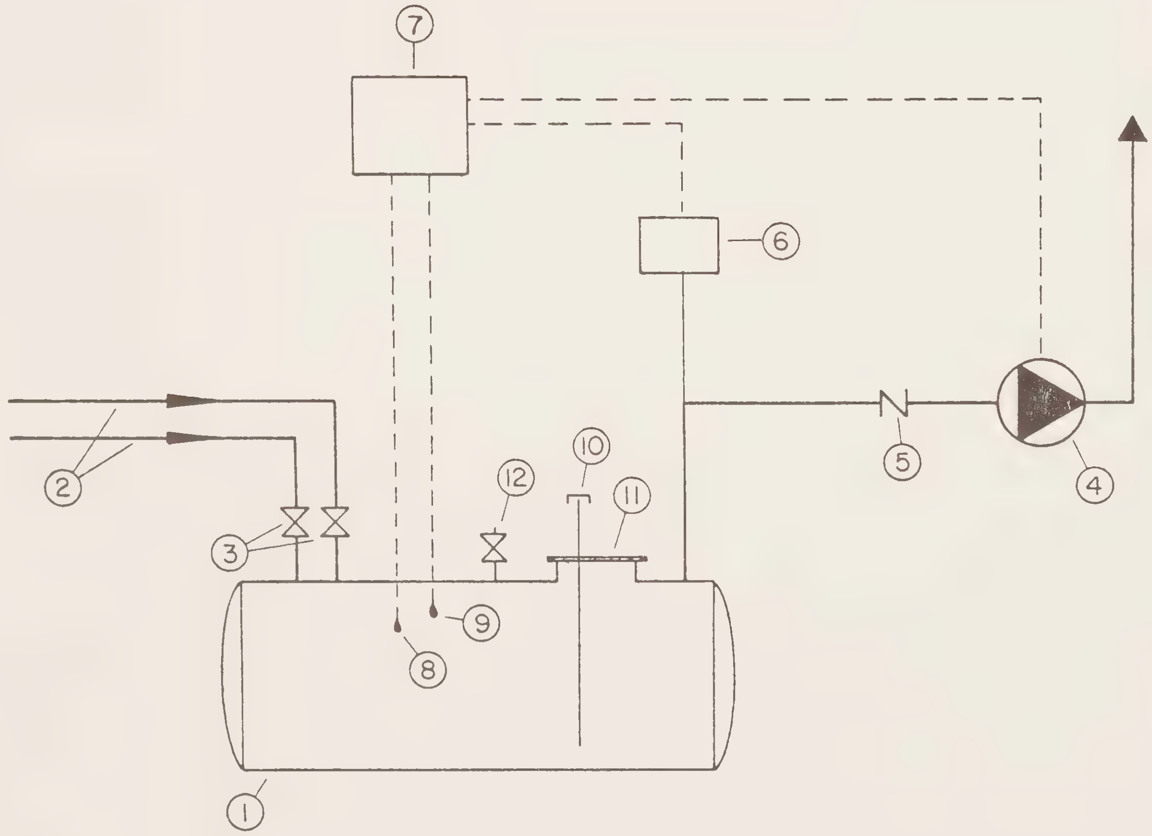


Fig. 1.30 ELECTROLUX TRANSFER UNIT



1 collection tank

2 black water vacuum mains

3 shut off (isolating) valves

4 vacuum pump

5 check valve

6 vacuum switch

7 control panel

8 liquid level sensor (high level warning)

9 liquid level sensor (block switch)

10 standpipe

11 access cover

12 vacuum relief valve

Fig. 1.31 COLLECTION STATION FOR A BLACK WATER HOLDING SYSTEM — SCHEMATIC

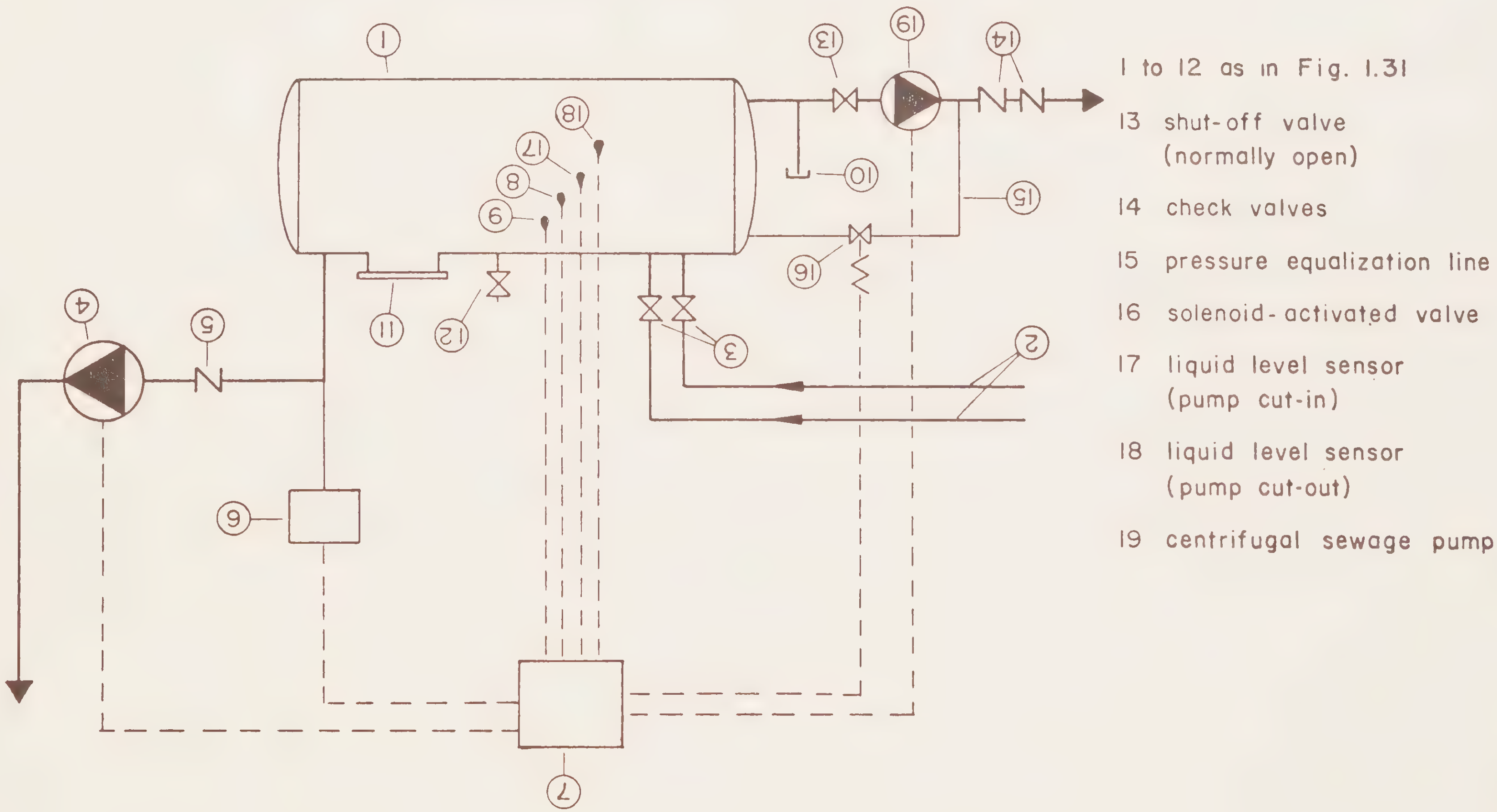


Fig. 1.32 COLLECTION STATION FOR PUMPED DISCHARGE WITHOUT VACUUM RELEASE — SCHEMATIC

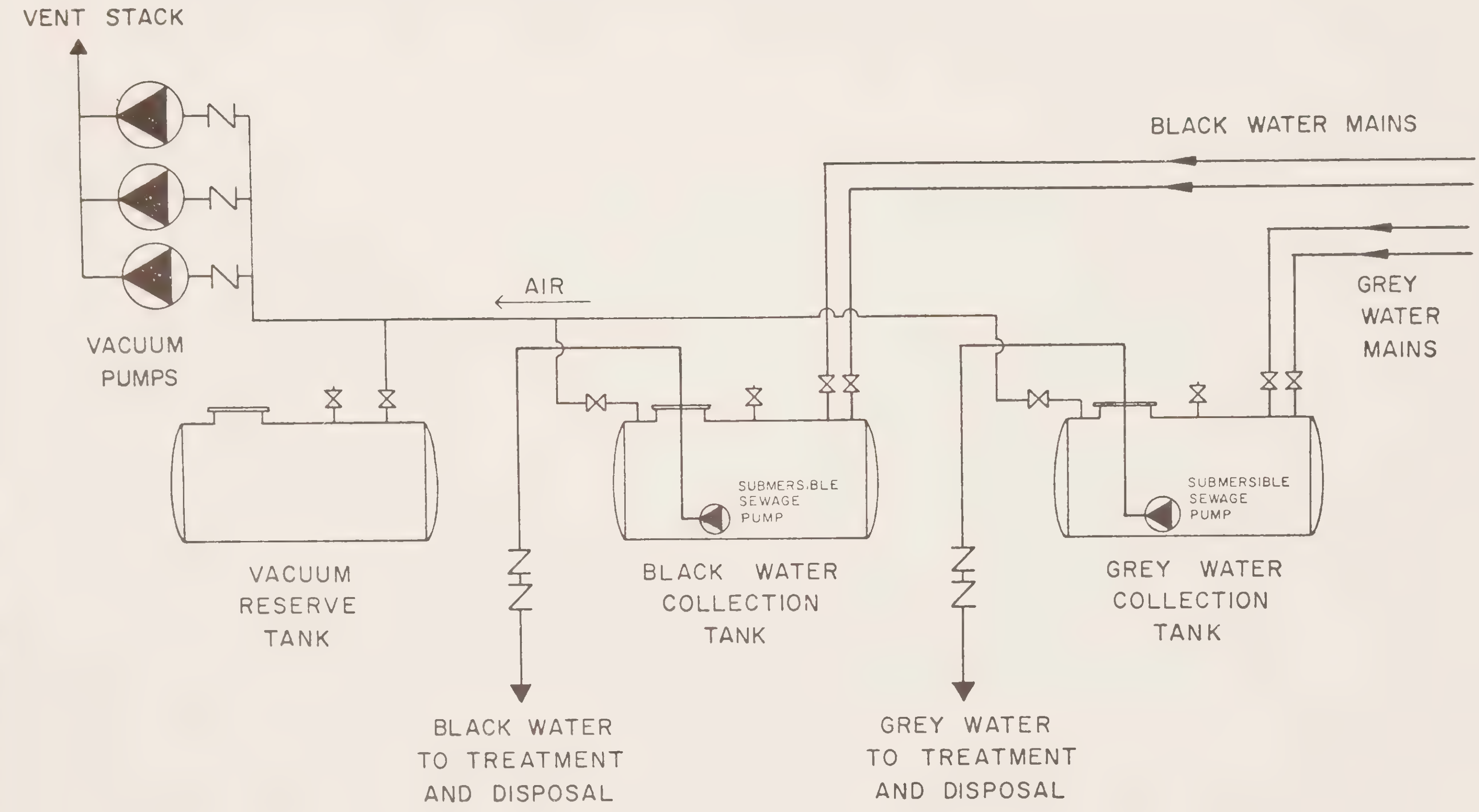


Fig. 1.33 COLLECTION STATION FOR THE TWO-PIPE SYSTEM — SCHEMATIC

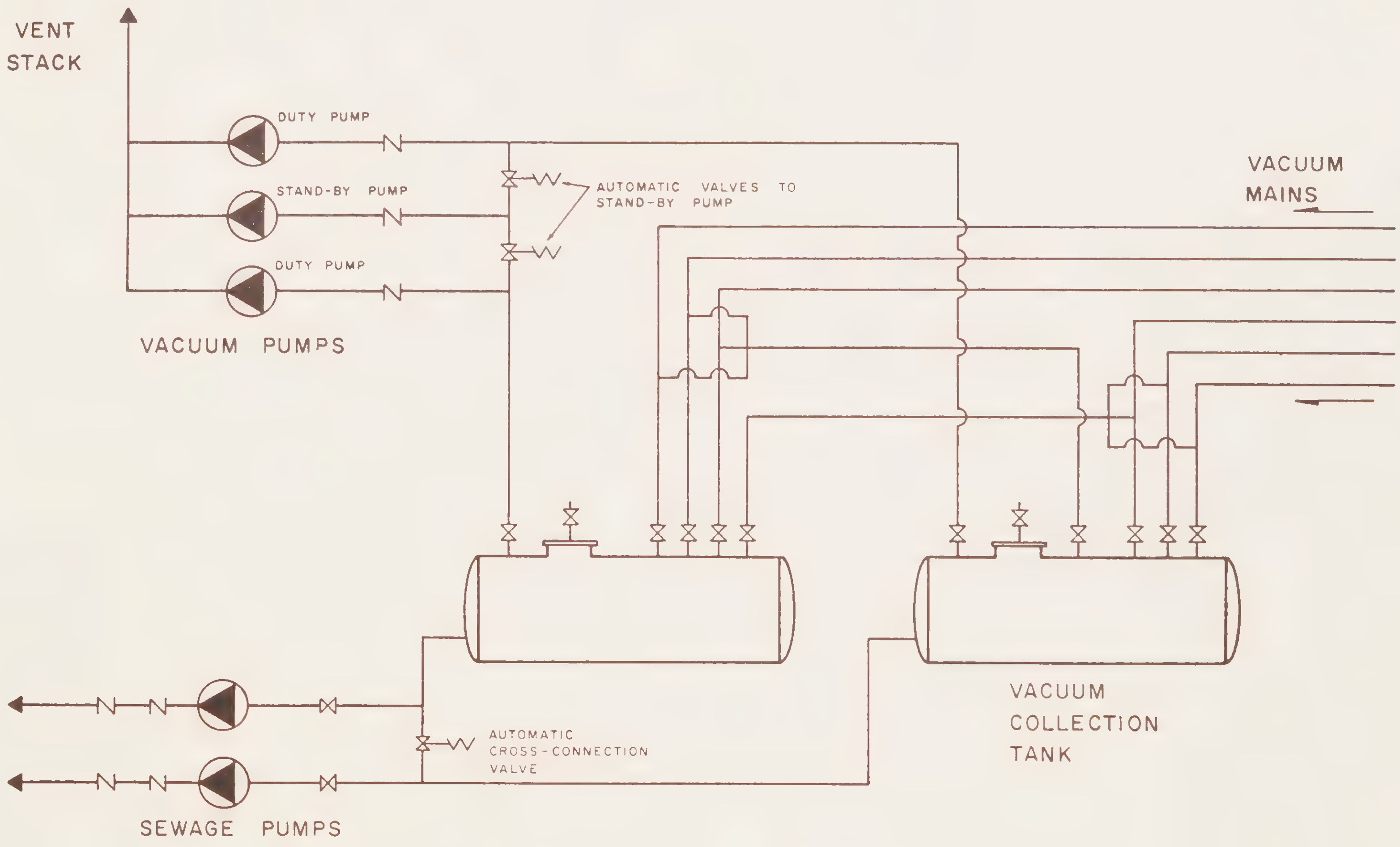


Fig. 1.34 COLLECTION STATION FOR THE ONE-PIPE SYSTEM
— SCHEMATIC

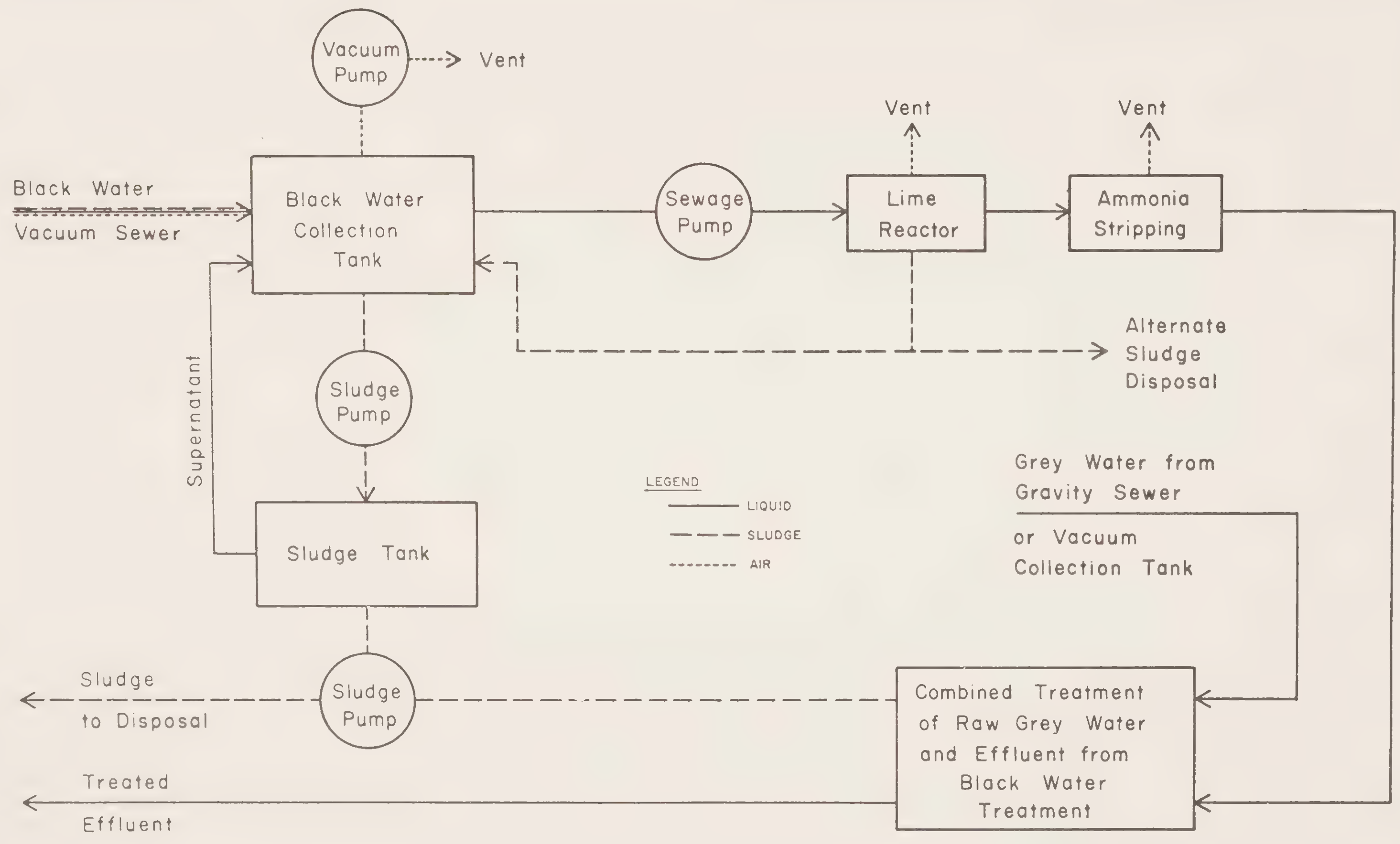


Fig. 1.35 LILJENDAHL BLACK WATER TREATMENT FOLLOWED BY COMBINED TREATMENT

Chapter II

Vacuum Sewer Systems in the Bahamas

2.1 Introduction

2.1.1 *History:*
Several vacuum sewer installations have been built in the Bahama Islands, see Appendix 1. Black water systems and two-pipe systems have been applied in a variety of installations ranging from a geriatric hospital to a night-club and from luxury apartments and hotels to low-cost housing developments. The smallest installation consists of three vacuum toilets and the largest should have approximately 1,500 vacuum toilets when completed.

The vacuum sewer system has proven particularly beneficial in the Bahamas. Several of the islands suffer from water shortages and much of the topography is fairly flat. Most of the installations are on New Providence Island which contains the capital, Nassau, and which has a resident population of about 100,000, about half the total population of the Bahamas. During the tourist season, which now lasts almost year-round, the total population, including tourists, increases considerably. During 1971, it was estimated that the water demand on New Providence Island was about 6½ MGD (30 million litres/day) but the maximum possible supply rate was only 5 MGD (23 million litres/day); consequently, the water supply must be restricted (ref. 2). The water source consists primarily of lenses of fresh water found floating on the salt water underlying the island. They are located mostly in the western part of the island and the maximum lens thickness is only 20 feet. Flash evaporators are now being used to supplement the fresh groundwater supply by desalinating brackish groundwater; but even when the evaporators are in constant use, the cost of water will remain relatively high.

All the vacuum sewer systems in the Bahamas were built by Livaco Bahamas Limited, a now-defunct division of the Standard Plumbing Company of Nassau, which obtained the Caribbean franchise for the vacuum system from Mr. J. Liljendahl before AB Electrolux became the owners of the system. The first installations were completed in 1965 and the latest were completed in 1970. Maintenance work is now carried out by Standard Plumbing and by individual owners.

Although the vacuum sewer concept seems ideally suited to Bahamian requirements and despite the fact that most of the owners and users of the systems appear satisfied, no vacuum systems have been installed since 1970. The government is not, at this time, willing to approve further installations in government buildings and housing estates, a decision apparently based on users' complaints and problems experienced in the low-cost government housing projects, the Big Pond Subdivision and Yellow Elder Gardens on New Providence Island. Problems arising from these installations are not necessarily due to inherent weaknesses in the principal characteristics of the system; but as it was still in its early stages of development, certain aspects of design and construction techniques were not as carefully applied as they would be at the present time. In addition, it appears that poor maintenance by government crews had permitted the equipment to deteriorate over a period of about five years.[1] During 1971 and 1972, the vacuum sewer installations at Big Pond and Yellow Elder Gardens were repaired and improved under the direction of Mr. B. Foreman, the Training Engineer of the Ministry of Works, Water and Sewerage Division. With proper maintenance the renovated systems should prove acceptable to the Bahamian Government and possibly lead to the lifting of the present ban on further construction of vacuum sewer systems.

2.1.2 *Geriatric Hospital:*
A government-owned geriatric hospital was completed in 1965 on New Providence Island. The 150-bed hospital is serviced by a black water vacuum system which includes 30 vacuum toilets, two urinals, and four bedpan washers. Grey water is conveyed by conventional plumbing to disposal wells. The black water collection station contains one vacuum reserve tank and two collection tanks used as gravity separation units. The supernatant is collected through overflow lines in a small cylindrical tank from which it is pumped to disposal wells. The sludge is periodically removed from the collection tanks by scavenger truck. This black water system originally included biological treatment (ref. 15) which apparently consisted of anaërobic digestion. A fourth large vessel was used to store the supernatant prior to discharge to the disposal wells but this tank no longer is in use. Two vacuum pumps are used in the collection station. Each pump is used for one month and is stripped and cleaned during alternate months. The only problem experienced with the installation is an occasional blockage in the black water pipes.

2.1.3 *Anchorage Hotel:*
The Anchorage Hotel in Nassau was originally designed for conventional plumbing but considerable cost savings led to construction of a gravity grey water system and a vacuum black water system. The 114-room hotel is serviced by a collection system consisting of one horizontal collection tank, one vertical vacuum reserve tank, two vacuum pumps, and

[1] In fairness to government crews, it should be recorded that no written operating or maintenance instructions of any kind were issued by Livaco when the plants were handed over to the government.

two sewage pumps. The wastewater is pumped from the collection tanks, without vacuum relief, to conventional sewers. The collection equipment is located in the basement of the building. Problems in this installation usually consist of pipe blockages caused by disposable diapers, sanitary napkins, rags, etc., although some vacuum toilets have required replacement parts.

Perhaps the most interesting aspect of the Anchorage installation is its cost, which has been estimated at two-thirds of the capital cost of conventional plumbing. Hotel Management is satisfied with the system's operation and it appears that any additional operating costs imposed by the vacuum system are more than offset by the money saved on water bills.[2] The system appears acceptable with its users, most of whom are American tourists.

2.1.4 *Delaporte Point Apartments:*

A black water collection and chemical treatment system has been incorporated into a luxury apartment development on Delaporte Point near Nassau. The black water is collected in two horizontal tanks from where it is pumped intermittently to a line reactor tank which is at atmospheric pressure. When the liquid level in the reactor reaches an upper limit the flow of wastewater is stopped and a recirculating pump cuts in automatically to mix the wastewater with lime. After sedimentation, an outlet valve opens automatically allowing the supernatant to flow into a deep disposal well where it is mixed with grey water (gravity collection) and saline groundwater. Excess sludge from the reactor tank can be transferred by vacuum to a storage tank using manually controlled valves. The lime sludge is allowed to settle in the storage tank. The supernatant is added to the disposal well and the remaining sludge is trucked away.

2.2 Yellow Elder Gardens Vacuum Sewer System

2.2.1 *Introduction:*

The largest government-owned vacuum sewer installation in the Bahamas is in a low-cost housing development called Yellow Elder Gardens (formerly known as the Harold Road Subdivision). It is located approximately two miles south of Nassau on New Providence Island. By mid-1972, approximately 450 single-family units and two schools were serviced by a two-pipe vacuum system using a single vacuum collection station.

Yellow Elder Gardens is built on low-lying flat ground. The local soil consists of a few feet of coarse sand overlying an oölitic limestone formation. The groundwater in the area is saline and tidal and at high tide the water table rises to within a few inches of the surface in some parts of the development.

[2]The water charges presently range up to $3.70 (Bah.) per 1,000 Imperial gallons.

2.2.2 *Collection Station:*

Figure 2.1 is a schematic diagram of the Yellow Elder Gardens vacuum collection station and is arranged to closely represent a plan view. Black water enters the station through two-inch PVC mains and, under normal operating conditions, is directed to black water collection tank number one. In this tank the majority of solids settle out and the remaining sewage flows through an overflow pipe into collection tank number two where further settlement occurs. The sludge collected in both tanks is removed periodically by scavenger truck and taken to a suitable facility.[3] The tanks are isolated and brought to atmospheric pressure for sludge removal. Liquid level sensors in black water collection tank number two control two sewage pumps which intermittently draw the wastewater from the tank and discharge it into a grease trap. One pump is used as the duty unit and the second as a stand-by unit; the discharge lines are separate from tank number two to the grease trap. Air is drawn off the vacuum collection tanks through a 4-inch PVC vacuum line which connects the collection tanks and a vacuum reserve tank to five liquid-ring-type vacuum pumps. The vacuum pumps draw their service liquid (water) from a fibre glass service liquid tank and return it, together with air from the collection tanks, through a four-inch PVC manifold. Air then escapes from the service liquid tank through an exhaust stack which extends above the roof of the pump building. The service liquid is cooled in a heat exchange unit which utilizes saline groundwater as the cooling agent.

Grey water enters the collection station through four, three-inch mains and is collected in a cylindrical steel tank. The grey water tank acts as both a collection tank and a vacuum reserve tank. It is placed horizontally in a pit and in order to limit the required lift in the system, about half the tank is below the station floor level. Discharge from the grey water tank is from a submersible pump which delivers the grey water to the same grease trap that receives the black water. From the grease trap the wastewater is allowed to flow into a 200-foot deep well where it mixes with salt water and is filtered by the limestone rock. The rock formation is sufficiently porous to allow the wastewater to flow into the well, rather than be injected under pressure.

[3]At the present time it is pumped into the ocean.

The Yellow Elder Gardens system was originally constructed using a Liljendahl black water treatment plant. Unfortunately, the treatment equipment was not properly maintained, and, as part of the recent renovation programme, it was discarded because it was beyond reasonable repair.

Although the new station is a considerable improvement over the original version, two changes are suggested. The collection station could be simplified, with some cost reduction, if the black water and grey water collection tanks were located in the same part of it. One vacuum reserve tank could then serve both systems, and consequently one bank of vacuum pumps and one set of vacuum pump controls could serve the entire station. Its size might also advocate the use of two grey water collection tanks and twin discharge pumps, as in the black water system. This would ensure continuity of service in the event of breakdowns and during maintenance operations.[4]

Photo 2.1 shows the Yellow Elder Gardens Vacuum collection station. The two black water tanks are to the left of the building with the vacuum reserve tank behind black water tank number two. The stand-by generator and the grey water collection tank are located in the enclosed court to the right of the building which contains the pumps and control equipment. The grease trap and well head are on the extreme right-hand-side of the picture.

2.2.3 *Sewers:*

The vacuum mains and service laterals at Yellow Elder Gardens are of PVC pipe joined with solvent-bonded couplings. The black water system consists of 1½-inch diameter laterals and 2-inch diameter mains and the grey water system of 2-inch laterals and three-inch mains.

This installation was one of the first of its kind in the Bahamas; consequently, the construction crews lacked experience, and poor construction practices apparently lead to operational problems. As gravity lines, the service laterals in the grey water system should have fallen from the houses to the vacuum mains. The black and grey water mains should have had high points between the transport pockets, with sufficient slope for gravity transport of the sewage into them. Unfortunately, the grey water service laterals were installed with little or no regard for grade and, in some cases, the trenches were back-filled while the mains were floating at high tide.

One significant problem in the black water mains is the formation of crystalline scale which tends to form at areas of increased headloss, such as at bends, in transport pockets, and at rough pipe joints. The formation apparently grows on the entire pipe wall and not only on the lower surface as is customary with scale of a sedimentary nature. This particular scale is believed to be the result of a sulphate bacteria growth. Scale formation does not occur in the grey water lines and it has been suggested by the public health laboratory staff of the Bahamian Government that soapy water prevents the growth of the sulphate bacteria. However, also it is suggested that the growth is dependent upon the nutritional and microbial conditions of raw sewage in the black water system. The high mineral content of the water used on this island may also influence the scale formation.

Scale is removed from the black water lines by washing with 20 per cent muriatic (hydrochloric) acid which is poured into the clean-outs once a month with dosages being determined by trial-and-error. During this monthly washing, the system remains in operation and acid is drawn through the lines by the normal operating vacuum. Despite the monthly acid washing procedure, acid soaking of the lines occasionally may be necessary for the removal of any scale which has formed. However, soaking has not been necessary since the washing procedure was initiated. It is not yet known what long-term damage the acid may be inflicting upon the pipe but there appears no significant effect over a period of about 12 months. Acid washing apparently is the only effective way of removing the scale.

Plugging of the PVC pipes by solid objects such as rags and disposable diapers is another problem with the black water system. Blockages may be eliminated, or greatly reduced, by the use of two-inch diameter service laterals and three-inch diameter mains. At one of the more recent installations, in the Delaporte Point Apartments, the larger pipe sizes were used and no blockages have been reported. An alternative solution to the plugging problem would be to adjust the vacuum toilets so that they require a 38 per cent to 40 per cent vacuum (60 per cent to 62 per cent atmospheric pressure in the system) before they can discharge. Early model vacuum toilets, which require only 25 per cent vacuum (75 per cent atmospheric pressure), were used in this installation. The greater pressure differentials ensured by a higher minimum operating vacuum permit the use of smaller pipe sizes with little possibiliy of blockages.

Air leaks are a third problem encountered with the black water system. A few may be caused by damaged pipes but the majority result from blockages of, or ruptures in, the diaphragm valve of the vacuum toilets. Since air leaks reduce the vacuum in the system they must be located and repaired with minimum delay. At present, they are located by isolating sections of the main, using an inflatable rubber plug and by checking every house in the section which contains the leak. Since some houses are not continuously occupied it is frequently difficult to locate and repair leaks. In a few cases at Yellow Elder Gardens it has been necessary to dig up a service lateral, and cut and cap it, to restore service to the rest of

[4]By early 1973, plans had been made to instal twin, open impeller, vacuum sealed, externally mounted grey water discharge pumps (ref. 22).

Photo 2.1 YELLOW ELDER GARDENS VACUUM COLLECTION STATION

the system. In future, all service laterals will be fitted with clean-outs which will facilitate the isolation of each house from the system by an inflatable rubber plug, and which will be useful in clearing blocked laterals. Using numerous isolating valves in the mains is not recommended because of the increased head-loss and the increased chance of blockages which will result. Plugging of the service laterals is the major problem experienced with the grey water sewers. Grease from kitchen sinks and soap scum settle out of the wastewater in the pipes. As indicated above, this problem has been made severe because service laterals do not have sufficient slope and in many cases they actually sag between the house and the grey water valve. A slope of at least one per cent would eliminate most problems of settlement since water would not tend to collect in the pipes. Also, it has been demonstrated that ''pulling'' the laterals by subjecting them to the vacuum in the main is often sufficient to remove the grease. If timed piston-type valves were used in place of float valves, the laterals would be pulled automatically each time the valves are activated.
and grey water mains at Yellow Elder Gardens consist of about 18 inches of straight pipe set below the elevation of the main by 45° elbows. The design of transport pockets has been modified since these earlier systems were installed (see section 1.4.2). Both black and grey mains at Yellow Elder Gardens were installed using grey PVC pipe. It has since become customary to use black PVC for black water lines and grey PVC for grey water lines.

2.2.4 *Collection and Vacuum Reserve Tanks:*
The two black water collection tanks, the grey water collection tank, and the vacuum reserve tank are welded steel units coated on the inside by epoxy-type paint. The black water collection tanks stand vertically on a concrete floor at ground level (Photo 2.2) as does the vacuum reserve tank used for the black water system. They grey water collection tank (Photo 2.3), which also serves as the grey water vacuum reserve tank, is placed horizontally in a pit about three feet deep.

Photo 2.2 BLACK WATER COLLECTION TANK No. 1

Photo 2.3 GREY WATER COLLECTION TANK

Wastewater levels in the collection tanks are controlled by Flygt float-type regulators. Black water tank number one contains a level sensor near the top of it which controls a block switch to shut down the black water system if it should fill with sewage. Black water tank number two contains a high level alarm sensor (upper float), a pump cut-in sensor (middle float), and a pump cut-out sensor (lower float). Similarly, the grey water tank contains a block switch sensor, a high level alarm sensor, and pump cut-in and cut-out sensors. Sensor levels in the black water collection tanks are not now set at the most efficient positions and proposed levels are shown in Figure 2.2 (ref. 22).

Table 2.1 gives the approximate sizes of the tanks in the Yellow Elder Gardens collection station.

Table 2.1
APPROXIMATE SIZES OF COLLECTION TANKS — YELLOW ELDER GARDENS

Tank	Circumference	Height or Length	Volume
Black Water Collection:	20′ 5″	10′ 2″	2,100 gal. (9,500 l.)
Vacuum Reserve:	18′ 8″	10′ 2″	1,800 gal. (8,000 l.)
Grey Water Collection:	15′ 9″	16′ 11″	2,100 gal. (9,500 l.)

Black water collection tanks, which sit in a vertical position and have conical bottoms sloping to central clean-out pipes, can be drained and cleaned easily. This advantage of vertical tanks is somewhat offset by the headloss involved in lifting the influent sewage to the top of the tanks. One compromise would be to place vertical tanks in a pit; however, in plants which dispose of sludge by scavenger truck, it would be necessary to depend on the truck's suction head to clean the tanks. In some locations it may be possible to choose a station site on sloping ground so that the collection tanks are low relative to the sewer mains and all drainage from the plant could be by gravity flow.

The grey water collection tank is mounted in a horizontal position. The problem of lifting large plugs of grey water several feet therefore has been avoided; however, cleaning the tank is very difficult. Settled solids must be removed by hand with a bucket and shovel, a problem which might be overcome by mounting horizontal tanks on a slight slope (5°) and including sludge draw-off points on the tank bottom. It may be possible in the future to utilize a large-circumference cylindrical tank which could be mounted vertically and still be low enough to prevent an excessive lift headloss. The unit also could be built with a conical bottom for sludge removal.

2.2.5 *Vacuum Pumps:*

The original vacuum pumps and motors used at Yellow Elder Gardens were manufactured in Europe. Replacements were made with English equipment obtainable at lower costs. The vacuum pumps (Photo 2.4) are presently Pepvac model FV3108 liquid ring type with stainless steel shafts and cast iron impellers (5.5 hp, 208 v., 3 ph., 60 cyc.). The service liquid used is tap water containing a substantial mineral concentration; consequently the pumps are subjected to the formation of considerable amounts of hard-water scale. Scale formation necessitates pump overhauls at least every six months, or as soon as the pump motor begins drawing too much current (16.5 amp. is the maximum limit).

The scale problem in the vacuum pumps may be reduced by using a water softening unit placed on the water service line and this will be added to the Yellow Elder Gardens collection station in the future. An alternative solution would be using oil as the service liquid and as it would become contaminated with condensed water vapour from the collection tanks, a centrifugal or gravity separator might be required. Although oil is not used at Yellow Elder Gardens because of its relatively high cost, it may be practical in other installations, particularly in cold climate areas. When compared with hard water as a service liquid, either oil or soft water, will prolong the lives of pumps and reduce the frequency of their overhauls.

The service liquid tank originally used with the vacuum pumps at Yellow Elder Gardens was located under the pumps and formed part of their base. Since the exhaust gases from the pumps are discharged into the service liquid tank, fumes escaped into the pump room, causing a considerable amount of corrosion, particularly to the electrical control equipment. At present, one large fibre glass tank is used for the service liquid and this is located outside the building and is covered to prevent heating by solar radiation. The heat exchange unit is manufactured by Alfa-Laval and consists of several parallel plates between which are passed the service and cooling liquids in alternate spaces. The unit may be opened easily for cleaning the plates with tap water and a stiff brush.

2.2.6 *Sewage Pumps:*

The black water discharge pumps used at Yellow Elder Gardens are PEP Mersey self-priming pumps (type M23, 3 hp., 208 v., 3 ph., 60 cyc.) (Photo 2.5). The impellers and wear plates are cast iron and the shafts are stainless steel. Unlike vacuum pumps which have fibre seals, these units have grease-lubricated mechanical seals. The pumps are controlled automatically by Flygt level sensors so that only the duty pump is used under normal conditions (either pump may be selected as the duty pump). The second pump acts as a stand-by unit which cuts in automatically if the first pump fails to start.

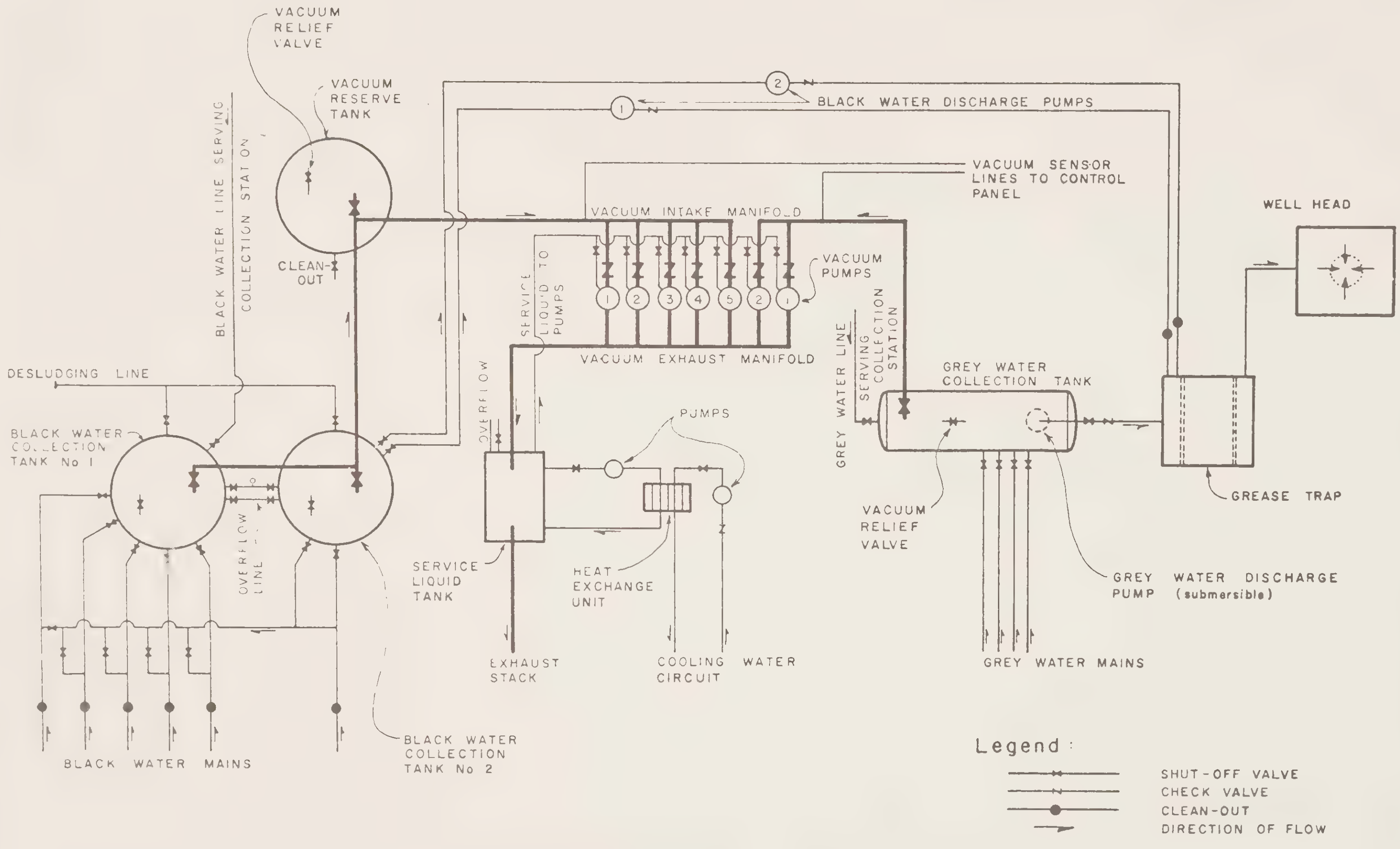


Fig. 2.1 YELLOW ELDER GARDENS VACUUM COLLECTION STATION — SCHEMATIC

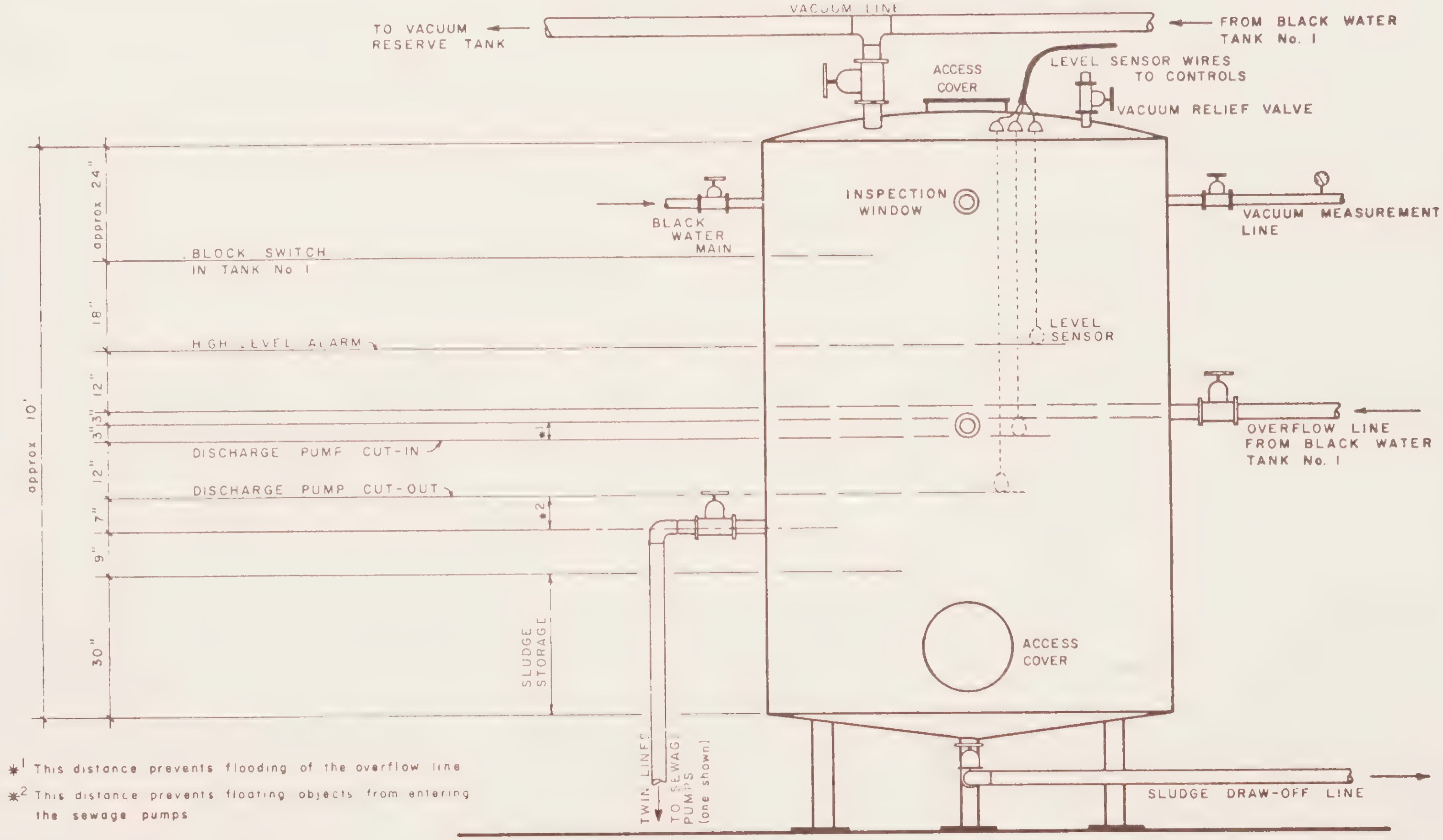


Fig. 2.2 BLACK WATER TANK No 2 (showing proposed levels)

Photo 2.4 VACUUM PUMPS

Problems experienced with black water discharge pumps involve cavitation and blockages. Since the pumps are working against the vacuum in the collection tanks they are forced to operate at suction heads approaching 20 feet of water; therefore, cavitation is difficult to avoid under the circumstances. The problem of blockages in the pumps may be avoided to a considerable extent by carefully selecting the sensor levels in the collection tank intake lines so that the lines are neither high enough to draw in floating solids, nor low enough to draw in settled solids.

The grey water discharge pump is a Flygt submersible pump. The original model used was Model B2101 but a replacement pump in use at present (Model B2102) was supplied although it does not have an open impeller and therefore is not suited to the purpose. The pump seals are carbide-type, with an oil bath between double seals. There is only one discharge pump in the grey water collection tank at the present time although this practice is not recommended.

2.2.7 *Grey Water Admittance Valve:*

The grey water admittance valve used in the Yellow Elder Gardens vacuum system is the float-type valve described in section 1.4.7. The valves are located in shallow access pits at the edge of the roads with each serving two houses and connected to their plumbing by gravity-flow service laterals.

The major problem associated with float valves is the failure of the rubber plug to seat properly, causing air leaks in the vacuum system. Solid objects in the grey water may create this seating problem; also, after a period of time, the rubber tends to become brittle and crack. The original float valve model had three narrow plastic strips which were attached to the inside wall of the chamber to act as guides for the float but they broke easily and were replaced on later units by three semi-circular supports.

There appears some controversy over the operation of the float valve. Theoretically, it should fall and close the effluent port when the water level in the chamber falls below a certain level; if this happens, small quantities of water and no air will be admitted to the vacuum mains. The overall result would be inefficient operation and possible waterlogging; in practice, the floats tend to "hang up" in the chambers allowing all of the grey water, and some air, to enter the vacuum mains. Also, poorly-seated plugs leak air into the mains, providing a means of grey water transport.

2.2.8 *Valves:*

The shut-off valves used in the vacuum sewer system at Yellow Elder Gardens are Saunders type KB cast iron, straight-bore valves with rubber diaphragms. Blockages caused by rags, etc., have occurred but their frequency does not suggest that the valves are appreciably more susceptible to blockages than the rest of the mains.

Two types of PVC non-return valves (check valves) are used, Plastiline ball valves (type 8332), and Electrolux flap-type valves. The ball-type valves are not ideally suited on vacuum lines as when in the open position they tend to vibrate, causing an audible knocking. They are used on the intake side of the vacuum pumps. The Electrolux flap-type valves consist of a PVC chamber with a rubber check flap reinforced with a stainless steel disk and pivoted on a stainless steel pin. This type of check valve must be situated so that the flap tends to close under its own weight. Although this type is appropriate for vacuum line application, it suffers from frequent failure of the rubber in the check flap. In some parts of the system these valves have been incorrectly used in pressure discharge lines, in which case the self-tapping screws holding the top of the chamber in place tend to tear out of the plastic and must be replaced with bolts.

2.2.9 *Liquid-level Regulators:*

Both black water and grey water collection tanks contain Flygt ENP-10 liquid level regulators. These are commonly called "float switches", although they are heavier than water and consist of a mercury switch and an eccentric lead weight enclosed in a pear-shaped PVC case. When submerged and suspended from the small end by its electric cable, the regulator takes a horizontal position because the large hollow end tends to float relative to the small weighted end. The eccentricity of the weight causes the mercury switch to be situated in the correct position while the "float" is horizontal. When hanging by its cable, free of the liquid, the regulator assumes a nearly vertical position.

The operation of the mercury switch is as follows:

1. When the regulator is vertical the circuit consisting of the red and white cables is completed (Fig. 2.3). If the red and white cables are connected to a power supply and to a warning device (bell or light) a signal can be produced for low level warnings. Similarly, it is possible to cut out a discharge pump or cut in a pump to fill a tank.
2. When the regulator is horizontal the circuit consisting of the red and black cables is completed and these may be used to cut in a discharge pump or cut out a filling pump, and for a high level alarm or block switch.

Although Flygt advertises that solids and scum get no grip on the glossy pear-shaped casing, the regulators in use in the black water collection tanks do accumulate a coating of solids. In addition to malfunctions caused by this coating, the regulators occasionally fail because of leaks at the cable-casing interface. In the near future the regulators will be replaced by B/W Floatless Liquid Level Controls which consist of electrode level-probes. This type

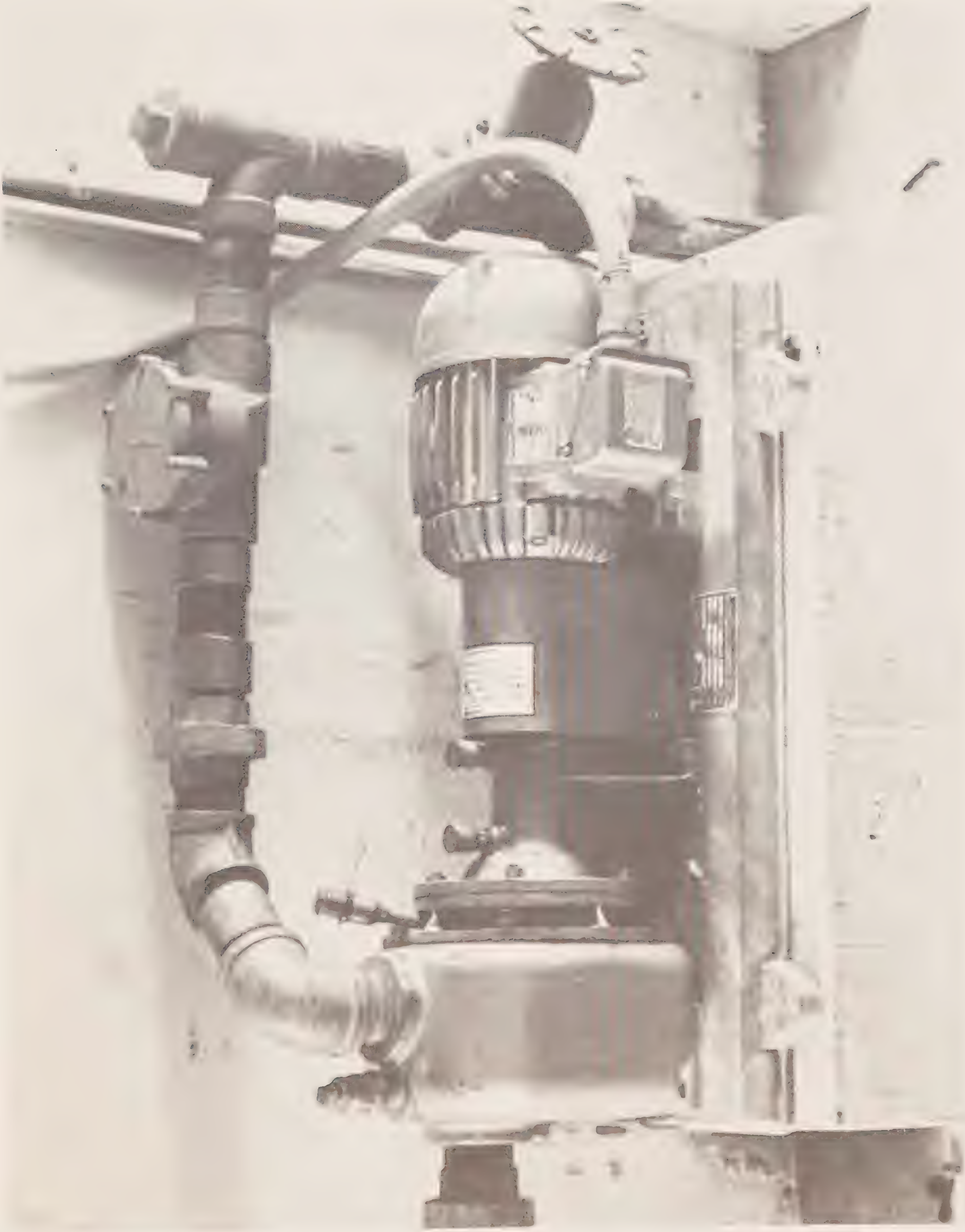


Photo 2.5 BLACK WATER DISCHARGE PUMP

of system utilizes the conductivity of the liquid being controlled and may be applied to vacuum or pressure vessels.

2.2.10 *Electrical Control Equipment:*
The electrical control equipment used at the Yellow Elder Gardens collection station is housed in two separate panels. One panel, known as the Livaco panel, was custom-built for the installation. It contains two vacuum switches, high level alarm switches, block switches, and controls for pump sequencing. The second panel, an Allen-Bradley panel, contains starters for the vacuum and discharge pumps.
The Livaco panel contains two Allen-Bradley vacuum switches, one to control the vacuum in the black water system, and one for the grey water system. They maintain the vacuum in each system between pre-selected upper and lower limits. The panel also contains multi-position switches for selecting the lead pumps for black water vacuum, grey water vacuum, and black water discharge. Once the lead black water and grey water vacuum pumps have been selected, the sequence controller triggers the pump motor starters in sequence, allowing a ten-second delay between each pump start-up to prevent overloads in the electrical system. A relay for the black water discharge pumps is used to cut in the stand-by pump if the lead pump fails to start after 1½ minutes from the time that the cut-in level regulator begins to signal. The Livaco panel also contains high level alarms (acoustic and visual) for the black water and grey water collection tanks and they are activated by Flygt level sensors. Block switches are included to shut down the vacuum pumps if the grey water or black water collection tanks should become filled. An alarm is also included to indicate a high service liquid temperature.
The Allen-Bradley panel (Allen-Bradley control centre model BUL798) contains 10 magnetic starters, one for each of the seven vacuum pumps and three discharge pumps. Also, for each pump, the panel contains a single-phase prevention device to prevent single-phase burn-out of the motors, an ammeter, an on/off/open isolator switch, and an on/off/automatic switch to control the starter of each pump.
The station is equipped with an Onan diesel generator used as a stand-by power source. It starts automatically when the main power fails and shuts off automatically about 20 minutes after the main power is restored. Twenty minutes of unloaded running is required to cool the generator. At this installation the stand-by generator supplies a more constant source of power than the power utility company with main voltage varying up to 15 volts per phase.

2.2.11 *Operations and Maintenance:*
Since both the Yellow Elder Gardens and Big Pond Subdivision vacuum systems were being re-built when this study was made, it is not possible to present an accurate account of the requisite amount of operational and maintenance work which is involved. Routine duties, which might be expected in a smoothly-operating vacuum sewer system, could not be separated from the work caused by the rebuilding programme and by old problems which had not yet been corrected since all work was being performed simultaneously by one crew. However, it is possible to estimate the normal requirements and operational characteristics of such systems from collection station records and from the experiences of the operators. Appendix II presents some pertinent operational details about the Yellow Elder Gardens vacuum sewer system and draws a few conclusions concerning operational and maintenance jobs and costs. The cost of any system depends not only on its characteristics but on certain factors related to the location of each installation. Appendix II is intended as a guide for cost estimation, rather than as a definitive statement, and it briefly may be summarized in the following statements.
The Yellow Elder Gardens vacuum sewer system provides two-pipe wastewater collection (without treatment) for about 450 single-family detached houses and two schools. A vacuum sewer system of this size and type would, under smoothly-operating conditions, involve the following:

1. power consumption of about 400 kw.hr./day;
2. a full-time crew of two men (one semi-skilled labourer and one foreman):
   - number of hours per year (not including engineering and management):
     - foreman: about 1,000 hours (he should be capable of running more than one station)
     - labourer: about 2,000 hours
     - other personnel: about 250 hours
3. other requirements include:
   - water supply
   - one vehicle (pick-up truck)
   - the use of one scavenger truck (about 3½ hours per week)
   - various consumable materials (acid, lime, disinfectant, grease, etc.)
   - replacement parts
   - building maintenance.

2.2.12 *Capital Cost:*
The actual capital cost of the Yellow Elder Gardens vacuum sewer system is not available. It may have been as low as 50 per cent of the cost of a comparable conventional system, but a 20 per cent to 30 per cent saving may be a more reasonable estimate.
The savings in capital cost achieved by the use of vacuum sewers depends on the type of system used and on the type of conventional system which would be required under the same conditions.
Livaco Bahamas Limited estimated the cost of vacuum and gravity wastewater systems for a development consisting of one-family two-bathroom

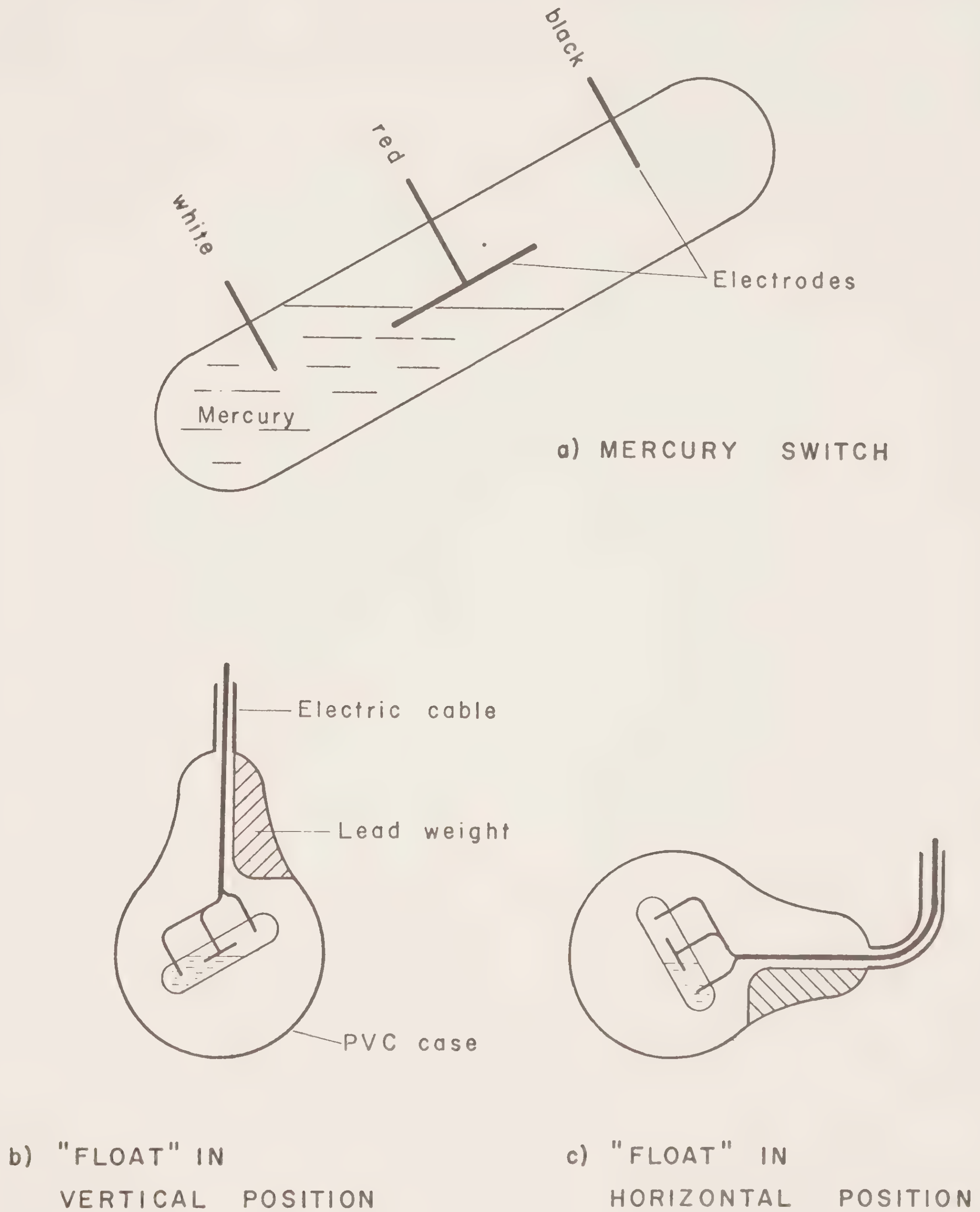


Fig. 2.3 FLOAT-TYPE LIQUID-LEVEL SENSOR — SCHEMATIC

residences (ref. 32). For a development of 220 to 250 houses the estimated costs, in Bahamian dollars,[5] were $720 per unit for the vacuum system and $1,784 for a septic system. The vacuum system estimate included $174 for pipes, $126 for labour, and $420 for a black water collection and treatment system plus a grey water collection system. The gravity system included $272 for pipes, $252 for labour, and $1,260 for a septic tank and tile field. This estimate results in a saving of 60 per cent of the septic system cost.

[5]One Bahamian dollar equals approximately one Canadian dollar. The report is undated but the estimate is probably in terms of 1965 or 1966 prices.

Chapter III

Theory and Design

3.1 Theory

3.1.1. *Introduction:*

Vacuum sewers are capable of transporting wastewater along an essentially horizontal grade and, within certain restrictions, up-grade transport is also possible. This characteristic leads to greater flexibility in sewer design, but it must be remembered that vacuum systems possess certain inherent limitations which preclude their use as a cure-all for common design problems. The length, capacity, and lift potential of vacuum sewers are limited by the available pressure differential.

Little or no technical material has been published about vacuum wastewater transport. The vacuum sewer system, most of which is covered by patents,[1] is being developed by private business concerns. The patent-holders are understandably inclined to protect whatever theoretical and experimental data they have obtained. However, it is possible to approximate the characteristics of flow in vacuum pipes using accepted techniques of hydraulic analysis.[2] This report includes calculations based on a simple analytical model as a method of approximating the headloss in pipes carrying wastewater by vacuum transport. The results of those calculations are then compared to corresponding results obtained using procedures outlined by AB Electrolux (ref. 4).

3.1.2 *Two-phase Flow Analysis:*

Vacuum transport of wastewater may be analysed using techniques developed for the study of one-dimensional two-phase flow. ''Two-phase flow'' is any flow involving two states or phases of matter (gas-liquid, solid-liquid, solid-gas). The term ''two-component flow'' is used to describe flows involving two separate chemical substances. For example, a steam-water flow is two-phase and not two-component, but an air-water flow is both two-phase and two-component. Therefore, if wastewater is assumed to be a single component, vacuum wastewater transport may be considered a two-phase two-component situation.

Two-phase flow analysis can be performed in a number of ways, some more complex than others. Correlation of experimental data in terms of chosen variables is a convenient way of obtaining design equations. This method is reasonably accurate providing that the correlations are applied to situations similar to those used to obtain the original data. Simple analytical models may also be of use and although they do not consider the details of flow, they are helpful in predicting design parameters and in organizing experimental results. For example, the homogeneous model replaces the components of two-phase flow with a single-phase pseudofluid which has average characteristics. The conventional methods of analysing single-phase flow can then be applied to the pseudofluid.

3.1.3. *Discussion of Flow Theory:*

The frictional headloss created by the two-phase flow of air and water in a pipe is greater than that created by the water component alone flowing at the same volumetric-flow-rate in the same pipe. Conversely, with a given pressure differential, the inclusion of air in a water-carrying pipe reduces the liquid transport capacity of the system; therefore, if capacity were the governing factor, full-pipe flow would be utilized in the design of vacuum sewers. However, the available driving force, about one-half atmospheric pressure, is not sufficient to maintain an acceptable transport velocity. It has been determined by Electrolux that the transport velocity should be at least three feet per second (1 m./sec.) for one-pipe systems; 1½ feet per second (0.5 m./sec.) for grey water systems; 33 feet per second (10 m./sec.) for black water systems; and that the time required to accelerate plugs of wastewater from rest to the transport velocity should be short (i.e.: negligible with respect to transport time). In this way sediment deposition and pipe clogging may be prevented.

If a pressure differential of one-half atmosphere is applied to a long column of water in a small-diameter pipe the resultant velocity will be low. However, if that same pressure differential were applied to a short column of water, a plug of water, the resulting velocity would of course be much higher. If these plugs can be made to follow each other in a pipe, with an appropriate headway, the system can be made to deliver the same quantity of flow as with full-pipe flow, but the transport velocity would be greater. The overall area of contact between water and the pipe wall in a given length of pipe would be reduced, tending to reduce headloss; but the increased velocity offsets this tendency since headloss is proportional to the square of velocity.

To illustrate the difference in frictional headloss, the headloss caused by the liquid component in two-phase flow may be estimated as follows:

[1]Presumably, certain aspects of the system are patented but the basic concept is not. A patent search is advisable prior to further studies.

[2]A thorough analysis of all aspects of hydraulics related to plug-flow is recommended.

1. pipe-friction equation (Darcy-Weisbach equation):

$$h_L = fLV^2/2gD \qquad (1)$$

where: h_L = frictional headloss (ft. of water)
f = friction factor
L = length of pipe (ft.)
V = velocity of liquid (fps)
g = acceleration due to gravity = 32.2 ft/sec²
D = pipe diameter (ft.)

2. using the ratio of plug length to headway:

$$h_L = fL\left(\frac{L_l}{s}\right)\frac{V^2}{2gD} \qquad (2)$$

where: L_l = length of liquid plug[3] (ft.)
s = plug spacing (ft.)
= length of one liquid plug (L_l) plus one air space (air cushion) (L_g)

3. velocity:

$$Q_l = Q\,\text{total}\left(\frac{L_l}{s}\right) \qquad (3)$$

$$= VA\left(\frac{L}{s}\right)$$

$$V = \frac{4\,Q_l\,s}{L_l\,\pi\,D^2} \qquad (4)$$

where: Q_l = volumetric flow rate of the liquid (cfs)
Q total = total volumetric flow rate (cfs)
= volumetric flow rate of liquid (Q_l) plus volumetric flow rate of gas (Q_g)
A = cross-sectional area of pipe (ft²)

4. substituting equation 4 in equation 2:

$$h_L = fL\left(\frac{L_l}{s}\right)\frac{(4\;Q_l\;s/L_l\,\pi\,D^2)^2}{2\;g\;D}$$

$$= \frac{8\;f\;L\;Q_l^{\;2}\;s}{\pi^2\;g\;D^5\;L_l} \qquad (5)$$

For the same liquid flow rate "Q_l", full-pipe transport would produce a headloss of:

$$h_L = fL\left(\frac{Q_l}{A}\right)^2 / 2\;g\;D$$

$$= \frac{8\;f\;L\;Q_l^{\;2}}{\pi^2\;g\;D^5} \qquad (6)$$

It is now obvious that the headloss in full-pipe flow and the water component of headloss in plug-flow differ by the factor (S/L_l) and by the difference in friction factors resulting from the different velocities. An air-to-water ratio of 4:1 produces a plug-spacing-to-plug-length ratio of 5:1, but the friction factor changes relatively little particularly at high transport velocities. The water component of headloss in plug-flow is therefore greater than the headloss in the same size pipe carrying the same liquid volumetric-flow-rate under full-pipe conditions. The air component of headloss must in some way be added to the water component to obtain the actual headloss created by plug-flow; sections 3.1.4 and 3.1.5 will discuss the total frictional headloss in two-phase plug-flow transport.

[3]also referred to as "liquid slug"

The most convenient way of expressing the headloss in plug-flow systems is as a function of the headloss in full-pipe systems carrying the same quantity of water per unit time. The ratio between the two-phase frictional loss and the related single-phase frictional loss is known as the two-phase multiplier, denoted by the symbol $Ø^2$.

$$-\left(\frac{dp}{dz}\right)_{F\ \text{two-phase}} = Ø^2\left[-\left(\frac{dp}{dz}\right)_{F\ \text{full-pipe}}\right] \qquad (7)$$

$$h_{L\ \text{two-phase}} = Ø^2\ h_{L\ \text{full-pipe}} \qquad (8)$$

where: z is measured along the pipe centreline

$-\left(\frac{dp}{dz}\right)_F$ = frictional pressure loss per unit length of pipe (pressure loss gradient) (psf/ft.)

The values of $Ø^2$ are always greater than unity.

3.1.4 *Friction Loss by Approximation:*

Wallis (ref. 42) describes a "slug-flow regime" which is characterized by a series of individual large bubbles of gas in a liquid-carrying pipe which almost fill the available cross-section (Fig. 3.1). A "unit cell" is considered to consist of one gas bubble and half of the liquid slugs on either side. The pressure drop caused by each liquid slug can be calculated by single-phase, single-component flow analysis techniques. The pressure drop along the cylindrical part of the bubble is zero and the pressure drop per bubble is due to effects at the ends of the bubble. It has been determined experimentally that the pressure drop per bubble is approximately equal to the pressure drop caused by the liquid in a length of about four pipe diameters. Therefore, an approximation of the pressure drop for one unit cell is:

$$\triangle p = (4\,C_f)\,\tfrac{1}{2}\,P_l\,j^2\,\frac{L_l + 4D}{D} \qquad (9)$$

where: $\triangle p$ = pressure drop (psf)
C_f = Fanning friction factor = f/4
P_l = liquid density (slugs/ft³)
j = volumetric flux (ft³/sec/ft²) = $(Q_g + Q_l)/A$

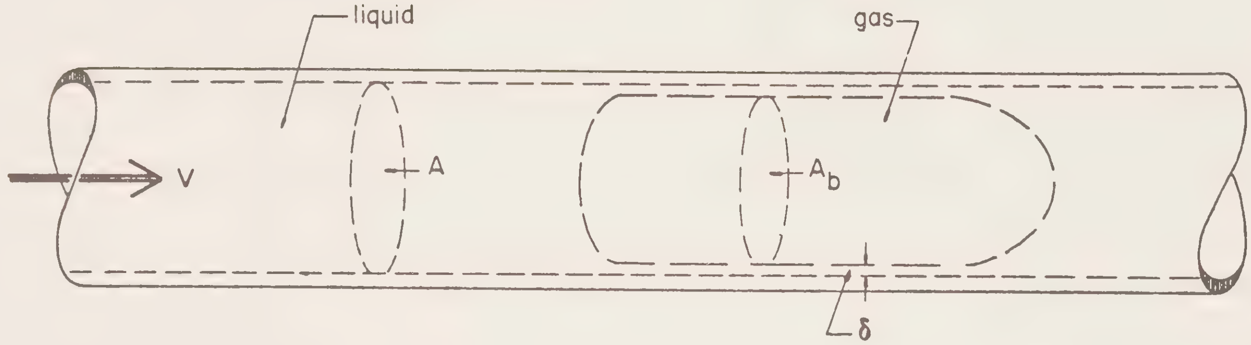


Fig. 3.1 SLUG FLOW

For long bubbles, the pressure gradient may be expressed as:

$$-\left(\frac{dp}{dz}\right)_F \frac{2\ C_f\ P_l\ j}{D}\left(j_l + \frac{4DA}{\nu_b C_1} j_g\right) \quad (10)$$

where: ν_b = the volume of one air bubble (ft^3)

C_1 = the ratio of pipe cross-sectional area (A) to bubble cross-sectional area (A_b)

j_l = volumetric flux of the liquid ($ft^3/sec/ft^2$)

= Q_l/A

j_g = volumetric flux of the gas ($ft^3/sec/ft^2$)

= Q_g/A

If the application is restricted to very long bubbles (four to eight times the liquid length at pipe pressures) the surface film thickness, δ, approaches zero and C_1 approaches unity. The equation may now be re-written as:

$$-\left(\frac{dp}{dz}\right)_F = \frac{2\ C_f\ P_l\ j}{D}\left(j_l + \frac{4DA}{\nu_b} j_g\right) \quad (11)$$

The equations presented above require a knowledge of the bubble volume. This quantity cannot be determined with reasonable accuracy because the exact nature of the flow regime depends on many factors including the pipe geometry, wastewater admittance valve adjustments, and sequence of valve activations. Unless the slug sizes and bubble sizes can be determined it would be preferable to use techniques which utilize the average air-to-water ratio in the pipes.

3.1.5 *Friction Loss by Homogeneous Model:*
A homogeneous model may be developed to provide two-phase headloss in terms of the average air-to-water ratio. It utilizes a hypothetical homogeneous pseudofluid to replace the two-phase two-component plug-flow conditions which actually exist in the vacuum pipes. The average air-to-water ratio is used to determine average physical properties which may be applied to the pseudofluid. Wallis (ref. 42) gave the following fundamental equations for homogeneous flow:

1. average wall shear stress:

$$\tau_w = C'_f\,(1/2)\,P_m\,V^2 \quad (12)$$

where: τ_w = average wall shear stress (psf)

P_m = mean density ($slugs/ft^3$)

C'_f = two-phase homogeneous friction factor (which must be evaluated — many methods of evaluation are possible)

2. frictional pressure gradient:

$$-\left(\frac{dp}{dz}\right)_F = 2\ C'_f\ P_m\ \frac{V^2}{D} \quad (13)$$

3. substituting for P_m and V:

$$-\left(\frac{dp}{dz}\right)_F = \frac{2\ C'_f\ G\ j}{D} \quad (14)$$

where: V = j = $(Q_g + Q_l)/A$

$P_m V$ = G = $(W_l + W_g)/A$

= mass flux ($slugs/sec/ft^2$)

W = mass flow rate (slugs/sec)

The conditions governing plug-flow may be substituted into the equation of the pressure gradient.[4]

1. volumetric flux, j:

Q_l = volumetric flow rate of the liquid (cfs)

$$Q_g = Q_l\left(\frac{L_g}{L_l}\right)$$

$$Q_l + Q_g = Q_l\left(1 + \frac{L_g}{L_l}\right)$$

$$j = \frac{Q_l}{A}\left(1 + \frac{L_g}{L_l}\right) \quad (15)$$

2. mass flux, G:

$$G = \frac{W}{A} = \frac{W_l + W_g}{A}$$

$$W_l = Q_l\ P_l$$

$$W_g = Q_g\ P_g$$

$$= Q_l\ P_g\left(\frac{L_g}{L_l}\right)$$

$$G = \frac{Q_l}{A}\left(P_l + \frac{L_g}{L_l} P_g\right) \quad (16)$$

3. Therefore, the pressure gradient is:

$$-\left(\frac{dp}{dz}\right)_F = \frac{2\ C'_f\,Q_l^2\left[P_l + \frac{L_g}{L_l}P_g\right]\left[1 + \frac{L_g}{L_l}\right]}{A^2\quad D} \quad (17)$$

The two-phase homogeneous friction factor (C'_f) must now be evaluated. One suitable method is to substitute an expression of equivalent viscosity in the Reynolds number (N_R) and then determine the friction factor as for single-phase flow. McAdams' equation for equivalent viscosity is:

$$\frac{1}{\mu} = \frac{x}{\mu_g} + \frac{1 - x}{\mu_l} \quad (18)$$

where: μ = dynamic viscosity ($lb.sec/ft^2$)

x = quality

= mass flow rate of the gas (W_g) divided by the total mass flow rate (W)

= $W_g/(W_l + W_g)$

[4]The following derivations and estimations in section 3.1.5 were produced specifically for this report.

The Reynolds number then becomes:

$$N_R = GD/\mu$$

$$= \frac{Q_l \ D}{A}\left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right]\left[P_l + \frac{L_g}{Ls} P_g\right] \quad (19)$$

and it could be applied to a single-phase friction chart. However, for this purpose it is preferable to obtain an expression for C'_f rather than a value, and therefore the Blasius equation for smooth pipes will be used as an approximation. The Blasius equation is valid for Reynolds numbers between 3,000 and 100,000. A simple check verifies that, at velocities above the minimum allowable for one-pipe systems (three fps), the Reynolds numbers fall mostly within that range.[5] As plastic pipe has a low relative roughness the assumption of a smooth pipe should not introduce a large error. The Blasius equation is:

$$C_f = 0.079/N_R^{\frac{1}{4}} \quad (20)$$

and therefore:

$$C'_f = \frac{0.079 \quad A^{\frac{1}{4}}}{Q_l^{\frac{1}{4}} \ D^{\frac{1}{4}}\left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right]^{\frac{1}{4}}\left[P_l + \frac{L_g}{L_l} P_g\right]^{\frac{1}{4}}} \quad (21)$$

The frictional pressure gradient then becomes:

$$-\left(\frac{dp}{dz}\right)_F = \frac{0.158 \ A^{\frac{1}{4}} \ Q_l^2 \left[P_l + \frac{L_g}{L_l} P_g\right]\left[1 + \frac{L_g}{L_l}\right]}{A^2 \ D\,(Q_l D)^{\frac{1}{4}}\left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right]^{\frac{1}{4}}\left[P_l + \frac{L_g}{L_l} P_g\right]^{\frac{1}{4}}} \quad (22)$$

A similar expression may be derived for full-pipe flow of a liquid using the same pipe and the same liquid volumetric-flow-rate as above.

$$h_L = f L \left(\frac{Q_l}{A}\right)^2 / 2 g D$$

$$h_L/L = 4C_f \left(\frac{Q_l}{A}\right)^2 / 2 g D$$

$$-\left(\frac{dp}{dz}\right)_F = 2 \, C_f P_l \ Q_l^2/DA^2 \quad (23)$$

where: C_f = one-phase friction factor
$= 0.079/N_R^{\frac{1}{4}}$

$$N_R = \frac{P_l \, Q_l \ D}{A \quad \mu_l}$$

$$C_f = 0.079 \left(\frac{A \quad \mu_l}{P_l \quad Q_l \quad D}\right)^{\frac{1}{4}}$$

Therefore:

$$-\left(\frac{dp}{dz}\right)_F = \frac{0.158\,(A\,\mu_l)^{\frac{1}{4}}}{(P_l \quad Q_l \ D)^{\frac{1}{4}}} \ \frac{P_l \ Q^2}{A^2 \quad D} \quad (24)$$

The two-phase multiplier, $Ø^2$, is obtained by dividing the two-phase pressure gradient (equation 22) by the one-phase pressure gradient (equation 24).

$$Ø^2 = \frac{\left[1 + \frac{L_g}{L_l}\right]\left[P_l + \frac{L_g}{L_l} P_g\right]^{\frac{3}{4}}}{\mu_l^{\frac{1}{4}} \, P_l^{\frac{3}{4}} \left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right]^{\frac{1}{4}}} \quad (25)$$

The quality, x, may be expressed as:

$$x = \frac{P_g \ \frac{L_g}{L_l}}{P_l + P_g \frac{L_g}{L_l}} \quad (26)$$

since: $x = W_g/W$
$W = W_l + W_g$
$W_l = Q_l \quad P_l$
$W_g = Q_l \ \ P_g \left(\frac{L_g}{L_l}\right)$

If the air-to-water ratio in the pipe, expressed above as (L_g/L_l), is designated as γ the expression for $Ø^2$ may be simplified.

$$Ø^2 = \frac{\left[1 + \gamma\right]\left[P_l + \gamma \quad P_g\right]^{\frac{3}{4}}}{\left[\mu_l \quad P_l{}^3\right]^{\frac{1}{4}}\left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right]^{\frac{1}{4}}} \quad (27)$$

where: $x = \dfrac{\gamma \, P_g}{P_l + \gamma \, P_g}$

Typical values of density, viscosity, and the air-to-water ratio may be used to determine the range of $Ø^2$ values obtained with equation 27. For this purpose, the following assumptions will be used:

1. The system is assumed to be in isothermal equilibrium.
2. The liquid will be assumed to have the properties of water at 50°F. ($P_l = 1.940$ slugs/ft^3; $\mu_l = 2.735 \times 10^{-5}$ lb.sec/ft^2).
3. The gas will be air at 50°F. The viscosity of air is assumed to be constant at any pressure ($\mu_g = 3.68 \times 10^{-5}$ lb.sec/ft^2).
4. The air-to-water ratio at pipe pressure is obtained from the NTP ratio by correcting for the differences in pressure and temperature.
5. The density of air in the pipes is obtained from the density at 50°F and atmospheric pressure ($P_g = 2.42 \times 10^{\ 3}$ slugs/ft^3) according to the equation $\nu_1 P_1 = \nu_2 P_2$.

The values obtained may be compared to $Ø^2$ values used by AB Electrolux in the design of one-pipe vacuum mains. The comparison is shown in Table 3.1 and an example of the calculations used to obtain the $Ø^2$ values from equation 27 is given in Appendix III. The Electrolux values were taken from a chart (ref. 4) but its derivation was not explained in the literature.[6]

[5] at 3 fps, 50°F, air-to-water ratio in the pipe of 4:1, 3″ Ø pipe, pipe pressure ½ atmosphere: NR for water (plug-flow) = 53,400; NR for air (plug-flow) = 2,600; NR for water (full-pipe) = 10,700.

[6] The authors do not intend to imply that the Electrolux chart was necessarily derived using the method described in this paper.

Table 3.1

COMPARISON OF $Ø^2$ VALUES FOR ONE-PIPE VACUUM SEWERS

Air-to-Water Ratio @ NTP	Pipe Pressure (atmospheres)	$Ø^2$ as calculated	$Ø^2$ from Electrolux
2:1	0.50	4.7	4.7
4:1	0.50	8.1	8.2
1:1	0.75	2.2	2.2

3.1.6 *Theoretical Approach to Lift Headloss:* According to Wallis (ref. 42) the pressure drop created by upgrade transport in two-phase flow may be expressed in terms of the mean density as follows:

$$-\left(\frac{dp}{dz}\right)_G = P_m \quad g \cos \Theta \qquad (28)$$

where: Θ = angle to the vertical (wedge angle)

P_m = the mean density of the substances in the pipe

= the density of the pseudofluid which possesses characteristics equal to the weighted average of the characteristics of the materials being transported.

This equation also may be written as:

$$-\left(\frac{dp}{dz}\right)_G = g \cos \Theta \frac{1}{\upsilon_l + x \upsilon_{l\,g}} \qquad (29)$$

where: υ_l = specific volume of the liquid

$\upsilon_{l\,g}$ = specific volume of the liquid relative to the specific volume of the gas

$$= \frac{1}{P_g} - \frac{1}{P_l}$$

For example, if the air-to-water ratio at NTP is 2:1 and the pipe pressure is ½ atmosphere, the pressure drop per foot of lift may be calculated as follows:

g = 32.2 ft/sec²

P_l = 1.940 slugs/ft³

P_g = 0.00121 slugs/ft³

x = 0.00249

$$-\left(\frac{dp}{dz}\right)_G = 32.2 \times 1 \times \frac{1}{\frac{1}{1.940} + 0.00249\left(\frac{1}{0.00121} - \frac{1}{1.940}\right)}$$

$$= 32.2/2.57$$

$$= 12.5 \text{ (psf/ft)}$$

In terms of head of water, the loss is:

$$-\left(\frac{dh}{dz}\right)_G = 12.5/62.4 = 0.20 \text{ ft./ft.}$$

To elaborate further on the preceding example, assume that the friction headloss in a given length of pipe has been determined at 5.4 feet (1.6 metres). In a one-pipe system, the collection tank vacuum head is usually controlled to fluctuate between 19.7 feet (6 metres) and 23.0 feet (7 metres) with an average applied head of 21.3 feet (6.5 metres). Without timer-controlled admittance valves, the vacuum head at the transfer unit has been measured at an average of 4.9 feet (1.5 metres). Therefore, the available head which may be used for wastewater transport is 21.3 − 4.9 = 16.4 feet (5 metres). With a friction loss of 5.4 feet (1.6 metres) the system would then be capable of lifting the equivalent of 11.0 feet (3.4 metres) of hydraulic head. At an air-to-water ratio of 2:1 (NTP) and pipe pressure of half atmosphere, 11.0 feet of available head permits the system to lift 11.0/0.20 or 55 feet (16.8 metres).

The above analysis indicates that vacuum sewers have a much greater lift capacity than that acknowledged by the Electrolux design procedures (ref. 4). Electrolux states that the maximum permissible lift in the one-pipe system is 16.4 feet (5 metres) and that the headloss caused by vertical lifts is equal to 50 per cent of the lift height. At the minimum recommended air-to-water ratio (2:1 at NTP) the headloss due to lift is, according to the above derivation, about 20 per cent of the lift height; at larger air-to-water ratios the lifting capacity would be increased.

In the black water system the air-to-water ratio is much larger than in either the grey water or one-pipe systems, and consequently the transport velocity and lift capacity are also greater. If a vacuum toilet admits about 1⅓ quarts (1.5 litres) of wastewater plus about 3½ cubic feet (100 litres) of air into the vacuum sewer system per flush, the air-to-water ratio would be 66.7. Using this air-to-water ratio and a pipe pressure of one half atmosphere, equation 29 produces a lift pressure loss of about 0.96 psf/ft. or a lift headloss of only 0.016 ft./ft.

With vertical transport, one factor which must be considered is the spacing of transport pockets. Gravity acts directly against the accelerating force of the pressure differential in vertical pipe sections. Acceleration and transport velocity are therefore less than in horizontal pipes and the pressure differential necessary to initiate movement is greater. In vertical transport, gravity does not have the tendency to disrupt the liquid plug as it does in horizontal pipes, and plugs moving uphill tend to be more stable than plugs moving horizontally. This tendency to greater plug stability will partially compensate for the greater resistance to motion; however, at some point the plug will break down and must then be trapped in a transport pocket. In progressing upstream in a vacuum main from the collection tank, the available driving head decreases due to accumulated headloss. Therefore, the vertical spacing between transport pockets may of necessity be decreased as the distance from the collection tank increases. Local irregularities in the flow regime may influence the size of the liquid plugs and the pressure differential and, in turn, influence the pocket spacing.

The required spacing probably can be determined best by experimentation. Electrolux has set the maximum rise between pockets in the black water system at five feet (1.5 metres), and the rise in grey water and one-pipe mains is established by the pipe profiles (see section 1.4.3).

3.1.7 *Discussion of Flow Regime:*
Design procedures must be based on average conditions in the vacuum mains; however, the actual flow conditions are far from the steady progression of uniform-size plugs suggested by the use of averages. The following paragraphs will attempt to illustrate what actually happens inside vacuum sewers.
Vacuum toilets and timed wastewater admittance valves admit into the vacuum pipes a plug of water followed by a certain volume of air. Provided the valve remains open the water is pushed along the pipe by atmospheric air pressure; but when it closes, the driving force consists of the pressure differential in the main between the air upstream and downstream of the liquid plug. As the plug moves downstream, the air volume between it and the admittance valve increases causing the upstream pressure to decrease; the plug eventually slows down and collapses. If there is a clear passage to the collection tank, the air is drawn out of the pipe by the vacuum pumps. If there is a water-filled transport pocket downstream, it expands to fill the available pipe volume, increasing the pressure in that part of the main. The exact pressure created depends of course on the amount of air admitted to the system, the original pressure in the pipe, and the volume into which the air may expand. This action causes a stepwise increase in pressure from the collection tank to the farthest end of the main.
Each stationary liquid plug in its transport pocket becomes "set up" by the pressure differential across it until this differential increases to the point at which the plug moves out of the pocket. When the plug is in motion, it compresses the air between it and the next plug downstream, possibly setting that plug into motion. Plug-flow in vacuum mains is therefore a "stop-and-go" phenomenon involving a lag in response between the points of admission and the collection tank.
The exact behaviour of wastewater in a vacuum main is extremely complex. It depends not only on the applied vacuum and the air-to-water ratio but also on the quantities of air and wastewater entering the system as well as the sequence of valve activations, and other physical factors such as pipe profile and roughness, and the number of bends and other obstructions in the main.

3.2 Design Practices
3.2.1 *Introduction:*
The following section outlines the design procedures used by Electrolux for black water systems, grey water systems, and one-pipe systems. The design of tank volumes, and the selection of vacuum pump capacities and discharge pump capacities, consist of simple balances between inflow and outflow quantities. The design of the vacuum mains is based partly on theory and partly on empirically-derived system capacities, with safety margins provided where appropriate.

3.2.2 *Design of Pipe Systems:*
The procedure used for the design of the one-pipe vacuum system is outlined below (ref. 4).
1. The pipe network is planned to determine pipe lengths and the differences in elevation for each section. The total negative difference in static head (that is, the total lift) is not permitted to exceed 16.4 feet (5 metres). The total lift includes the lift from the lowest level in the buffer tank to the main, the sum of all lifts in the main, and the lift into the collection tank; falls cannot be subtracted from lifts because the fluid is not continuous.
2. The design flow is equal to twice the mean daily flow.

$$q_d = 2\,N\,q_m\,\frac{1}{24}\,\frac{1}{60}$$

where: q_d = design flow (GPM)
N = number of people served
q_m = mean flow per person per day (GPCD)

This quantity is less than the peak flow used in the design of conventional gravity sewers. Conventional design practice would produce larger pipe sizes, and transport velocities below that required to prevent sedimentation in the mains. Buffer tanks, with a capacity equal to the mean daily flow from each house, are used to even out the load placed on the vacuum mains. The average daily per capita wastewater contribution, q_m, is determined according to local practice.
3. The available pressure differential in the system is equivalent to 23.0 feet (7 metres) of water at or near sea level. If 6.6 feet (2 metres) is allowed for fluctuations in the collection station and for activation of the wastewater admittance valves, 16.4 feet (5 metres) is available to compensate for headloss in the pipes. From this 16.4 feet (5 metres) it is necessarily to subtract the headloss due to lift in the pipe network and the remaining head is available to overcome pipe-friction losses. The headloss due to lift is estimated at 50 per cent of the total static head and as the total static head is not permitted (arbitrarily) to exceed 16.4 feet, the maximum total headloss due to lift is 8.2 feet, leaving 8.2 feet as a minimum to overcome pipe-friction losses. Therefore, depending on the pipe profile, there will be between 8.2 feet and 16.4 feet of friction headloss permitted in each main.

4. The friction headloss per unit length of pipe is calculated knowing the headloss due to lift. For example, if the headloss due to lift is 6.6 feet (2 metres), the friction loss may total 9.8 feet (3 metres). This allowable friction headloss is then divided by the total length of the vacuum pipe.
5. The mean pressure differential in each section of the system can now be found by subtracting the accumulated headloss from the total available pressure differential.
6. The air factor, $Ø^2$, can be determined from an Electrolux graph for each section of the pipe network using the mean pressure differential for that section and a suitable air-to-water ratio.
7. The frictional headloss for a pipe flowing full (at the design flow) may be determined by dividing the actual allowable friction headloss (calculated above) by $Ø^2$.
8. Knowing the frictional losses created in the equivalent full-pipe flow condition, the appropriate pipe sizes can be selected for each section using one-phase full-pipe design practices.
9. The velocity in two-phase flow is obtained by multiplying the one-phase velocity by $(1 + \gamma)$ where γ = the air-to-water ratio and $(1 + \gamma)$ = the plug spacing-to-plug-length ratio. $(L_l + L_g)/L_l$). If the two-phase velocity is below 3 fps (1 m./sec), a new air-to-water ratio must be selected and $Ø^2$ must be re-determined. The air-to-water ratio usually varies between 1:2 and 1:4 at NTP and for each application it can be chosen to suit the pipe profile to ensure system reliability.

The grey water vacuum mains are designed by the procedure described above for the one-pipe system. The timed grey water valves are usually adjusted to provide an NTP air-to-water ratio of 1:1. This lower ratio results in lower transport velocities and consequently lower friction losses relative to the one-pipe system, but the lift headloss is increased by decreasing the air-to-water ratio. However, the lift headloss used for design purposes is also one-half of the lift height.

The black water vacuum mains are designed by a method similar to that used for the other systems. In this case, the design curve used by Electrolux provides friction loss directly as a function of loading and pipe diameter. Therefore the two-phase multiplier, $Ø^2$, must be included in the curve as a constant. Application of the theoretical equations derived in section 3.1.5 indicates that the black water system design curve may have assumed that the pipe pressure is one-half atmosphere throughout the system and that the NTP air-to-water ratio is based on 1.5 litres of wastewater and 100 litres of air per flush. Lift loss in the black water system is assumed to be one-quarter of the lift height.

Safety margins are included in the design procedure in three ways. First, the lift headloss used for design is considerably greater than the theoretical values. Secondly, the effect of gravity in accelerating wastewater plugs in down-grade sections of pipe, and in transporting the broken plugs into the transport pockets, has not been included as an energy input. The third safety margin is provided by establishing relatively conservative standards for the horizontal and vertical spacing of transport pockets and by basing these standards on laboratory and field tests.

Chapter IV

Applications in Canada

4.1 Introduction

4.1.1 *System Variations and Applications:* Vacuum sewer systems are functioning satisfactorily in Scandinavia, the Bahamas and in other locations, and they are now being introduced in several other parts of the world, including Canada. The objective of this chapter is to consider the potential of vacuum sewers in Canada.

Most of Canada has abundant supplies of fresh water. In the foreseeable future there will be no widespread pressure to conserve water by replacing the conventional water closet. Therefore, the water conservation advantage of vacuum sewers does not appear of major importance for most parts of the country. However, the second advantage of the system, its ability to transport wastewater horizontally and to some extent up-grade, may be of more value. Probably it will be used in communities which would be extremely expensive to service with conventional sewers because of flat topography, high groundwater levels or rocky terrain. Some Canadian communities may consider the use of a one-pipe system as an economical alternative to conventional gravity sewers. Conventional fixtures and plumbing probably will be retained in all existing housing units where vacuum sewers are built. In new developments vacuum toilets may be used, although their primary purpose likely will be to decrease the load on the sewer system rather than to save water.

Directing attention away from the average Canadian community to more remote types of habitation will, to a considerable extent, change the conditions and priorities. Many isolated settlements located in harsh climates and/or on rugged terrain experience problems with water supply and pollution control. There, vacuum sewer systems could reduce water consumption and transport wastewater where conventional sewers would be impractical. In addition, the two-pipe version of the system may be used to facilitate efficient and thorough wastewater treatment, particularly in areas where the disposal of partially treated effluents would be undesirable. Vacuum sewers should prove both efficient and economical when used in such remote settlements as lumber and mining camps, temporary construction camps, cottage communities, and of course in arctic and sub-arctic communities.

The vacuum sewer system has other special applications which probably will find use in Canada. Already it has been applied to ships, trains, and mobile sanitary facilities in other countries. The marine applications have been quite successful, although markets for the others are presently in the early

stages of growth. Other special applications include industrial uses and the use of vacuum transport in building renovations. With the growing concern for environmental protection and the emphasis placed on recycling, many industries will be forced to separate sanitary wastewater from process wastewater and various process wastewaters from each other. The flexibility of vacuum systems permits waste separation with a minimum of delay and reconstruction in existing plants. Also, with minor modifications, one-pipe systems may be used with overhead sewers hung from factory ceilings to provide sanitary facilities in "islands" located in the middle of large production areas (ref. 8). Similarly, the flexibility of vacuum systems considerably benefits the renovation of buildings of all kinds, permitting freedom in the location of sanitary facilities.

4.1.2 *Costs:*
The actual cost of vacuum sewer systems in Canada cannot be determined until a few pilot installations have been built and operated there. It will depend on local labour costs, construction material prices, transportation costs, and on import duties for some items.

Experience in Scandinavia and the Bahamas has indicated that under conditions which favour the use of vacuum sewers, their capital cost is roughly two-thirds that of comparable gravity systems. However, each proposed installation will require individual consideration because of variations in the physical and economic factors which determine the ultimate cost of any system and because the type of vacuum system used will vary according to local requirements.

An Airvac booklet (ref. 36) estimates that the capital cost of a one-pipe vacuum sewer system is 20 per cent to 30 per cent less than the cost of an equivalent gravity system. This estimate is based on the use of inexpensive, light-weight, and small-diameter pipe in shallow trenches with the elimination of most lift stations and the substitution of clean-outs for manholes along the vacuum mains. It appears that this estimate does not apply in areas where very few lift stations, if any, would normally be needed; nor does it apply where the wastewater admittance valves used in the vacuum system are located outside the buildings serviced (as with most one-pipe systems serving conventional plumbing systems) for there the valves must be placed in manholes.

This uncertainty about the relative cost of vacuum systems is supported by a report written for the Rappahannock County Water and Sewer Authority by Martin, Clifford, and Associates (ref. 34). Based on estimates given in the report, a gravity sewer system for the Town of Sperryville, Virginia would cost approximately 30 per cent more than an equivalent one-pipe vacuum system. For the gravity system, standard manholes were listed at $325.00 each, and for the vacuum system, vacuum valves were listed at $200.00 each, but no manholes were included for the valves. To quote the report: "No manholes are required in the vacuum system, thus offering additional savings. However, the inclusion of the diaphragm valve at each service connection precludes some of these savings."

Maintenance and operational costs also depend largely on local conditions. The number of operators required depends primarily on the size and type of vacuum system considered but also will be influenced by such factors as user abuse and severity of the local climate. The cost of electric power can be estimated by determining the number, sizes, and operating periods of the vacuum and sewage pumps. The cost of replacement parts, vehicles, and consumable materials may be based on life expectancies and estimated consumption rates, as well as suppliers' price lists and transportation costs.

Accurate estimates of maintenance and operational costs in Canada will be obtained only after experience has been gained in one or more pilot installations; however, rough estimates may be obtained by applying appropriate unit prices to the items mentioned above. Appendix II is intended as a guide for cost estimation and is based on experience gained at the Yellow Elder Gardens vacuum sewer system in the Bahamas.

Comparisons of the operational and maintenance costs of vacuum sewer systems and equivalent conventional systems in Canada also may be produced when more experience is acquired. It has been reported (ref. 35) that, over a period of eight years, the first large-scale Swedish vacuum installation has produced lower operational costs than a conventional installation of the same size.

4.2 Applications in Temperate Areas

4.2.1 *Development of Vacuum Systems in Canada*
In considering potential Canadian applications (section 4.1.1), it is not surprising that the first installations planned and constructed in this country involve primarily the special applications of the system. By mid-summer of 1973 two marine installations and three trailer-mounted portable units were in operation; a third marine installation and two more trailers were under construction, as were three permanent land-based installations (Appendix IV). Other land, marine, and trailer installations were in the planning stage. The three land-based installations under construction in 1973 were all in recreational developments, two being camping areas and the third a cottage resort.

While the development of a Canadian market for these special applications appeared to be under way by mid-1973, the municipal applications of the system were beginning to show signs of acceptance. At least one of the planned installations mentioned above involved a residential sub-division in a

suburban area. This is planned for a group of single-family detached dwellings located in the valley of the Ottawa River in Ontario. The site is relatively level and the soil conditions are poor, with shale near the surface. A one-pipe vacuum system with pumped discharge to local gravity sewers would be an ideal solution to the servicing problems in similar locations.

4.2.2 *Recreational Areas:*
There are some 600,000 summer cottages in Canada and each year the number grows by an estimated 60,000 (ref. 29). Most of them are located near lakes and rivers and many use inadequate sewage systems. A recent survey of more than 4,500 lakefront cottages performed by the Ontario Ministry of the Environment indicated that only 65 per cent had satisfactory wastewater disposal systems. In addition to individual summer homes, many private, provincial, and national parks are becoming overcrowded to the extent that pollution levels are becoming a problem. Conventional sewer systems and treatment plants are not practical in remote, low-density recreational areas. In most cases the buildings are located in lake basins close to the shore where all wastewater would have to be lifted up-hill to reach a gravity collection system. The usual solution to the wastewater problem is septic tank decomposition and disposal to the soil through a tile field. To function properly such systems require about 1,500 square feet of permeable soil at least five feet deep and above the water table and such conditions are often not available.
Various modifications of the vacuum system may be applied to cottages depending on the existing conditions and local regulations. Collection and trucking of black water is the basic method. In some locations all wastewater may be disposed of by scavenger trucks after storage in holding tanks. Some cottage communities may use small chemical treatment plants for black water or collective septic or aërobic treatment of combined black and grey waters. Where cottages are built on steep lots, vacuum sewer systems using pump-discharge from the collection tanks may be used to lift wastewater a considerable height to reach conventional municipal sewers or access roads suitable for scavenger trucks.
Vacuum systems may be an acceptable and economical way of dealing with the pollution problem in recreational areas. The cost of a cottage vacuum system probably will not be excessive when compared to the cost of alternatives such as importing sand for tile fields or installing incinerating toilets (about $600 installed). This is also true when it is compared to the cost of the cottage and lot or to the prospect of not being permitted to build at all. Installation of the vacuum toilet and pipe could be handled as a do-it yourself project and even the simpler collection systems would not be too difficult for a knowledgeable handy-man (ref. 9, 11).[1]

4.3 Applications in the Arctic
4.3.1 *Introduction:*
Vacuum sewer applications in the Arctic may include most of the types of installations used in more southerly areas and in larger settlements they probably will prove economical for servicing residential and commercial developments. Another probable application of the vacuum sewer system is in mobile and permanent construction camps.
As stated previously, the major advantages of the vacuum sewer system are the possible water savings and the ability to transport wastewater economically in areas where topography and soil conditions make gravity transport prohibitive. To these advantages can be added a third factor which may prove decisive in the design of arctic services. In remote areas, the cost of transporting materials is a large percentage of construction costs. The pipe used for vacuum sewers has a small diameter and is considerably lighter than conventional sewer pipe; consequently, transportation costs can be significantly reduced.
Most arctic areas receive very little precipitation and the mean annual total varies from five to 15 inches (water equivalent). Surplus precipitation, that water which could be utilized without depleting the supplies of groundwater and surface water, amounts to less than four inches of rainfall over most of the Arctic. Obviously, surplus water is scarce in many areas, but obtaining it for consumption is also a considerable problem. From the air there appears an abundance of surface water in the north; however, most of the lakes and rivers are shallow and in winter the ice depth may exceed 10 feet. Unfrozen bottom waters, when found at all, contain the dissolved solids content of the entire water body and therefore are not suitable for drinking. Larger rivers such as the Mackenzie River provide a reliable source but, problems may be experienced with turbidity, pollution from upstream sources, and intake-clogging frazil ice. Groundwater is of very limited use and availabality. Water in the permafrost zone is of course frozen year-round; above the permafrost, in the active layer, the groundwater is predominantly or totally affected by the winter freeze-up. Intrapermafrost water occasionally can be found but the cause of its liquid state is usually its high dissolved mineral content. Subpermafrost water is frequently located at great depths and may be brackish or saline due to limited recharge from the surface or other more distant sources. Ice and snow are melted for water in some settlements but the cost of fuel or electrical energy, plus limited precipitation, would

[1]Small-size collection systems are available in Sweden as easily-assembled package plants. The same type of equipment probably will be made available in Canada.

make this source impractical for larger settlements. Since potable water is scarce in many parts of the Arctic, the reduction in water consumption permitted by the use of vacuum toilets may be a significant factor in the design of municipal services. Reducing the demand for water also will be beneficial in reducing the cost of the water distribution systems. In many locations ground conditions prevent the use of buried sewers and they frequently consist of either exposed bedrock or permafrost. Above-ground insulated ducts, called utilidors, therefore are used to carry services in many communities. Utilidors are insulated and heated and, because they carry gravity sewers, they are restricted to following hydraulic grade lines. In Inuvik N.W.T., for example, they are about 4 feet by 4½ feet in cross-section, cost about $230 per linear foot and carry water pipes, sanitary sewers, and central heating mains. Since vacuum sewers utilize small-diameter pipes and are not, to a large extent, dependent on grade, the design and construction of utilidors could be simplified and the cost reduced. The ability to construct small, low-cost, utilidors and to locate them on the ground surface, using insulating aprons or berms, would be of great importance in the construction and maintenance of arctic municipal services.

In sub-arctic climates[2] it is often possible to instal underground services, suitably modified but similar to those used in temperate regions. Vacuum sewers, insulated and placed underground, may prove economical in certain sub-arctic locations, particularly those which have problems with water shortages, topography unsuitable for gravity systems, and high transportation costs.

4.3.2 *Design Considerations:*

If vacuum sewers are to be adapted successfully for arctic conditions certain special design considerations must be included in the system. The principal concern will of course be protection against freezing in the severely cold winters. This section discusses some of the problems which must be overcome before vacuum sewers can be successfully applied in the Arctic.

4.3.2.1 *System types:*

The vacuum sewer system probably will be used in the Arctic principally as the one-pipe version to service the larger communities. Few communities have any sewage treatment facilities and if they do exist they generally consist of sewage lagoons (ref. 24). Therefore, two-pipe systems, and the sophisticated treatment techniques which may be applied to two-pipe effluents, likely will not be considered practical for several years. Black water systems leave disposal of the grey water to the discretion of the residents, and since tile beds and disposal wells are generally not feasible, wastewater would be dumped on the ground around each house. In smaller communities this method of grey water disposal probably will be sufficient since, combined with the use of a "honey bag" collection system for toilet waste, it is currently in use in many arctic communities. However, in centres large enough to have piped water supply and wastewater disposal, grey water should be disposed of in a more sanitary and aesthetic manner.

Black water systems may find use in communities served by trucking systems for water supply and wastewater disposal. While there is little reason to build black water mains and leave grey water disposal to the residents, black water holding systems may be beneficial as they can serve one house, a group of houses, or an apartment complex. They would benefit from the relatively small quantity of wastewater produced by the black water system but vacuum transport probably would not be as significan a factor in most cases; there, the vacuum system would face substantial competition from gravity-type toilets which are dsigned to use very little water.[3] Chemical toilets, incinerator toilets, and the present "honey bag" system are other alternatives for smaller communities.

4.3.2.2 *Technical considerations:*

Thermal insulation may be applied directly to the vacuum pipes; for example, where they are placed underground but not below the frost line. Insulation also may be used in the walls of a utilidor where vacuum mains are exposed to the heat supplied by water mains or heating systems which are inside. The insulation may be of any conventional type, including glass fibre or foam plastic; however, a new type of insulating concrete may prove beneficial. Expanded beads of polystyrene are used as the principal aggregate in a light-weight concrete to produce a durable material with excellent insulating properties (ref. 25, 36). It is stable when submerged in water, resistant to rotting, insect and animal attack, mechanical damage, and freeze-thaw cycles, and its unit weight may be varied to make pipes either float on water or remain buried in soils with high water tables. Polystyrene-aggregate concrete therefore may prove valuable for insulating underground sewer pipes and watermains.

It is also conceivable that this insulating material may lead to the design of a new, economical utilidor system. Service pipes could be located by hangers or spacers at regular intervals and cast within a solid mass of insulating concrete. The result would be a light, compact, durable unit which could be placed on or above the ground surface using gravel berms, piles, or aprons of insulating concrete. It would of course be necessary to provide access to the mains

[2]defined as a climate in which one to three calendar months have mean monthly temperatures above 50°F.

[3]Flush-O-Matic and Aqua-Jet are two such units (ref. 29).

for heating frozen pipes and/or for easy replacement of sections of utilidor in case of damage or freezing. Utilidors and individually insulated pipes may be heated in several ways. The fluids carried in them may be heated or the heat may be applied to the pipe walls by heat tracing systems. Utilidors which carry central heating pipes may be protected from freezing by allowing a calculated amount of heat to escape into the them through the insulation surrounding the heating pipes.

A certain amount of heat is added to domestic wastewater before it is discharged to the sewers and it may be sufficient to prevent freezing in the vacuum mains, providing the pipes are well insulated and the wastewater does not remain stationary in them for excessive periods. If design calculations indicate that this heat source is not sufficient to prevent freezing, additional heat must be supplied by one of the methods mentioned above. If central heating is not carried by the utilidor the best way to supply requisite heat may be by using heat-tracing tape as described in the following paragraphs.

Plastic or metal pipes may be heated by means of specially designed heating tape. Electro-Wrap, manufactured by Chemelex (ref. 3), consists of a thin strip of polyester or teflon containing flat copper conductors between which is a patented graphitic compound bonded between thin asbestos sheets. Current passes between the parallel copper conductors through the graphitic compound, causing uniform resistive heating over the surface of the strip. The Electro-Wrap strip has an adhesive back and may be bent to follow the shape of the pipe. Thermostats may be bound to the surface of the pipe and used to control pipe temperature by a switch controlling the current in the heating tape.

Heating tape is preferable to steam or wire tracing systems because it distributes heat over a broad surface of the pipe eliminating the possibility of local overheating, and because insulation is simpler and less expensive with the flat heating tape.

Heating non-metallic pipes generally is very difficult because of their poor thermal conductivity. Applied heat tends to overheat the pipe at the point of application and thermostatic control also is difficult. Thin wide strips of heating tape may be used to apply heat over a wide area of plastic pipe, and thermostats may be mounted directly on the tape thus eliminating wide fluctuations in temperature. However, when vacuum pipe must be heated to prevent freezing, lined metallic pipe is preferable to plastic pipe. The metallic outer shell of the pipe conducts heat readily around the pipe circumference. Plastic-lined steel pipe therefore may be preferable to PVC pipe in the Arctic.

In arctic installations it is essential that warm air enters the mains through air admittance valves. Slugs of warm air not only clean out the lines, to prevent the wastewater from standing too long and losing heat, but also will help to increase the temperature of the mains. If the mains are arranged in loops, starting and ending at the vacuum collection station, the air admittance valves may be located in the station and may admit room-temperature air into them. An alternative would be to design all mains to converge at one point, where a small heated building could be used to house the air admittance valves. The loop configuration may prove more practical, particularly if a single-main recirculating water supply system is combined with the vacuum sewer in a utilidor.

Other factors which must be considered include the following:

1. Temperature differentials of considerable magnitude between winter and summer and between winter air and heated pipes will require careful consideration of expansion and contraction in pipes and utilidor structures.
2. Buffer tanks and wastewater admittance valves must be placed inside heated buildings.
3. The collection tanks should be installed inside the collection station to facilitate maintenance operations during winter and to eliminate the need for tank insulation and in-tank heating elements.
4. Provision must be made for clean-outs in the vacuum pipes which provide easy access while preventing them from forming a major point of heat loss.

4.3.2.3 *Complexity:*

In 1965 it was stated by Drobny (ref. 24) that, with respect to arctic services, "The essential feature of any workable system will be simplicity." The shortage of trained personnel in remote areas can mean the failure of any system, regardless of its design excellence. At this point it is necessary to consider the one potential weakness of the vacuum sewer system in northern applications. It cannot be described as simple when it is compared to a conventional gravity sewer system. Even if lift stations and pressure sewers are added to the latter, the vacuum system still includes more mechanical and electrical equipment. Consequently, more training will be required to properly equip operators for the task of running a vacuum sewer system.

Perhaps a more reasonable comparison might be made between the vacuum sewer system and a piped water supply system. Both require roughly the same equipment including a pressurized pipe network, valves, pumps, and automatic sensing and control equipment. Any community served by a water distribution system, and probably by water and wastewater treatment systems, could be served by a vacuum sewer system without an excessive increase in the complexity of equipment.

Although the vacuum sewer system appears somewhat complex after a cursory inspection, its components are relatively simple. The starters and asso-

ciated control equipment would present no problems to an electrical technician, neither would the pumps to a mechanic nor the pipes and valves to a plumber. Its technical requirements actually may be of more benefit than hindrance in the Arctic, since maintenance jobs would be created for skilled and semi-skilled local workers.

4.3.2.4 *Types of housing:*

It is probably beneficial to consider the types of housing units for which vacuum sewers are proposed, or more generally, the type of housing used in the Arctic. The most expensive type of development to service is the privately-owned, single-family detached house. Buildings must be serviced by lengthy utilidor systems which are located along road rights-of-way or along special corridors or easements. The service connections to each building significantly add to the total utilidor length. A more economical scheme would be to run a utilidor through a group of detached houses, or preferably, construct semi-detached houses or townhouses in order to minimize the length of exterior utilidors. Multi-storey apartment buildings are of course the means by which a maximum number of users may be accommodated while requiring the minimum utilidor length.

The type of housing used must not only satisfy technical objectives but also it must be socially acceptable. Increasing construction costs and land prices in the more heavily populated parts of southern Canada recently have resulted in the construction of more apartment towers and townhouse developments at the expense of detached single-family homes. As higher-density housing becomes more widely accepted in southern regions there is no reason to believe that similar developments will not be accepted in the arctic, where rambling subdivisions are simply not practical.

It might be argued that placing services inside housing units will involve difficulties regarding maintenance, legal jurisdiction, etc. These potential problems may be minimized where government-owned units are rented or sold on a condominium basis, with provisions made for appropriate service maintenance by government or private agencies.

The major design consideration encountered when using intra-unit utilidors is the requirement for heating and insulation. In some cases, it may be desirable to maintain a fully heated and insulated utilidor both outside and inside the housing units. In this way unoccupied units may be closed and left unheated without endangering the services. Cost savings would result from the elimination of service laterals. An alternative solution would be to ensure that all, or part, of every unit remain above 32°F at all times; in this case, utilidor insulation may be reduced or eliminated inside the units.

4.3.3 *Noorvik, Alaska:*

The United States Department of Health, Education, and Welfare[4] plans to complete, by late 1973, a vacuum sewer installation in the Village of Noorvik, Alaska (ref. 39). The Noorvik installation consists of a one-pipe vacuum system, including vacuum toilets, with the vacuum mains housed in utilidors on the ground surface. Initially, the system will serve 18 houses, a school, and a clinic; 25 additional houses will be added at a later date. The Noorvik system will be monitored closely and probably will be followed by other vacuum sewer installations in Alaska.

The Noorvik utilidors are rectangular in cross-section with a height of only 12 inches and widths of from 16 inches to 36 inches, depending on the number of pipes carried in any particular part of the utilidor system. They carry 2½-inch PVC vacuum sewer mains, three-inch PVC water mains, and one-inch copper heat tracer lines. Insulation is provided by four inches of urethane and heat is supplied by the one-inch tracer system which contains an anti-freeze solution. Sufficient heat should be provided by the water and wastewater in the utilidor to prevent freezing under most conditions and the tracer system will be needed only for extremely cold weather or when the water supply system is not operating.

The utilidors are constructed to form loops which start and end at the collection station. Air admittance valves located inside the collection station are designed to admit controlled volumes of room temperature air into the mains at pre-selected time intervals. The use of air admittance valves ensures that transport in the mains is not delayed for prolonged periods of time, thus minimizing the chance of heat loss and freezing of the wastewater in the mains. The air which enters the mains also provides an additional source of heat in the utilidor.

In this installation the utilidors pass under the buildings served by the system. Service connections rise vertically from the utilidors and pass through the floors of the buildings. At floor level both the water and sewer lines are fitted with flexible hose connections to allow independent movement of the building and utilidor to prevent frost heave damage. The wastewater admittance valves (grey water valves) are located inside the buildings at floor level, thereby necessitating the location of all fixtures, notably the bath tub, at least 12 inches above the floor.

Transport pockets are provided in the vacuum mains in a special length of utilidor which is 16 inches high and is fitted with an access cover located in the top of the structure. The transport pockets are constructed from 45 degree Y branches and elbows and each pocket incorporates two clean-out plugs.

[4]U.S. Department of Health, Education and Welfare; Public Health Service; Sanitation Facilities Construction Branch; Alaska Area Native Health Service; Anchorage, Alaska.

Appendix I

Vacuum Sewer Installation in the Bahamas

Name	Year Completed	Details
1. Geriatric Hospital	1965	30 VTs[1], 2 urinals, 4 bedpan washers, deep well disposal
2. Big Pond Subdivision (low income housing)	1965	184 VTs (when complete); two-pipe systems; deep well disposal
3. Harold Road School (880 children)	1966	33 VTs; 8 urinals; connected to Yellow Elder Gardens collection station.
4. Robinson Road School (800 children)	1966	33 VTs; 8 urinals; deep well disposal
5. Harbour Mews Apts.	1966	83 VTs; chemical treatment
6. Bahamas Electricity Corporation	1966	19 VTs; connected to Big Pond collection station
7. Plastic Pipes Ltd. (demonstration unit)	1966	3 VTs
8. Yellow Elder Gardens (low income housing)	1967	383 VTs; two-pipe system; deep well disposal
9. Big Pond School (300 children)	1967	132 VTs; connected to Big Pond collection station
10. Anchorage Hotel	1967	132 VTs; black water collection with disposal to city sewer
11. Chertsey Apts.	1967	85 VTs; chemical treatment and deep well disposal
12. Blue Hill Rd. School	1967	29 VTs; connected to Yellow Elder Gardens collection station
13. Delaporte Point Apts.	1967	384 VTs; (when complete); chemical treatment with deep well disposal
14. Fortune Bay I Subdivision[2]	1967	approximately 260 VTs when complete
15. Fortune Bay II Subdivision[2]	1967	approximately 1,000 VTs when complete
16. Fortune Bay III Subdivision[2]	1967	approximately 1,500 VTs when complete
17. Arnold Palmer's Island Inn[3]	1968	167 VTs (when complete)
18. Dirty Dick's	1969	30 VTs; black water collection with disposal to city sewers
19. Yellow Elder Gardens[4] (extension)	1970	12 VTs
20. Harold Road School (extension)	1970	15 VTs; connected to Yellow Elder Gardens collection station

[1]VT (vacuum toilet)
[2]Grand Bahama Island } all other installations are
[3]Eleuthera Island } on New Providence Island.
[4]In 1972 Yellow Elder Gardens consisted of about 450 houses. Additional units were opened in 1973.

Appendix II

Operational Data — Yellow Elder Gardens Vacuum Sewer System

A2.1 Pump Operation

The data presented below was obtained from records maintained at the Yellow Elder Gardens collection station. The operating hours are totalled over 291 days from September 6, 1971 to June 23, 1972.

A2.1.1 *Black Water Vacuum Pumps:*

#1	2942 hr.	or	10.11 hr./day
#2	3037 hr.		10.44 hr./day
#3	2413 hr.		8.29 hr./day
#4	2584 hr.		8.88 hr./day
#5	2377 hr.		8.17 hr./day
average	2671 hr.		9.18 hr./day

A2.1.2 *Black Water Discharge Pumps:*

#1	306 hr.	or	1.05 hr./day
#2	176 hr.		0.60 hr./day
average	241 hr.		0.83 hr./day

A2.1.3 *Grey Water Vacuum Pumps:*

#1	5864 hr.	or	20.15 hr./day
#2	5876 hr.		20.19 hr./day
average	5870 hr.		20.17 hr./day

A2.1.4 *Grey Water Discharge Pump:*

954 hr. or 3.28 hr./day

A2.2 Quantity of Wastewater

A2.2.1 *Black Water Discharge:*

— pumping rate (measured by filling the grease trap) = 57.4 GPM
— average running time (from above) = 0.83 hr./day
— quantity of black water pumped = 0.83 × 60 × 57.4 = 2,800 GPD
— quantity of sludge removed from two black water tanks = 2,200 gallons/week = 310 GPD
— total quantity of black water received by the collection station = 3,100 GPD

A2.2.2 *Grey Water Discharge:*

— pumping rate (measured by filling the grease trap) = 109 GPM
— average running time (from above) = 3.28 hr./day
— quantity of grey water pumped = 3.28 × 60 × 109 = 21,500 GPD
— quantity of sludge removed from the grey water tank = negligible
— total quantity of grey water received by the collection station = 21,500 GPD

A2.2.3 *Wastewater Production Per Capita:*

— population (based on 450 houses at 5½ persons per house) = 2,475
— black water production = 1.25 GPCD
— grey water production = 8.69 GPCD

A2.2.4 *Discussion:*

The quantity of black water produced by the development is equivalent to about five flushes per person per day, which is a reasonable result. The basis for design is usually six flushes per person per day. Using water consumption data for 1971, the average water consumption in Yellow Elder Gardens is 67 gallons per lot per day, or about 12.2 GPCD. The total wastewater flow is, for comparison, about 9.9 GPCD. The difference (2.3 GPCD) consists of water which does not reach the sewer system and which is probably used for washing cars, watering lawns, and particularly in this case, for laundry operations using outdoor tubs.

A2.3 Power Consumption

A2.3.1 *Maximum Demand Estimate:*

A2.3.1.1 *Critical conditions:*

— four black water vacuum pumps operating
— one grey water vacuum pump operating
— one black water discharge pump operating
— one grey water discharge pump operating
— two cooling pumps operating
— one black water vacuum pump and one grey water vacuum pump starting simultaneously
— neglect lighting, fan, power tools, etc.

A2.3.1.2 *Motor data:*

— black water discharge:	10 amp. @ 208 v.
— grey water discharge:	27 amp. @ 208 v.
— vacuum pumps:	16½ amp. @ 208 v.
— cooling pumps:	8 amp. @ 115 v.

A2.3.1.3 *Calculations:*

Assume the instantaneous starting current of vacuum pump motors is six times the running current.

— black water vacuum:	4×16½×208	= 13,728
— black water discharge:	1×10×208	= 2,080
— grey water vacuum:	1×16½×208	= 3,432
— grey water discharge:	1×27×208	= 5,616
— cooling pumps:	2×8×115	= 1,840
— two motors starting:	2×6×16½ ×208	= 41,184
— total (watts)		= 67,880

Therefore, the expected peak demand is about 67.9 kilowatts.

A2.3.2 *Daily Consumption Estimate:*

A2.3.2.1 *Critical conditions:*
— five black water vacuum pumps operating
— two grey water vacuum pumps operating
— one black water discharge pump operating
— one grey water discharge pump operating
— two cooling pumps operating
— neglect lighting, fan, power tools, etc.

A2.3.2.2 *Operating periods:*
— as above (A2.1)

A2.3.2.3 *Motor data:*
— as above (A2.3.1.2)

A2.3.2.4 *Calculations:*
— black water vacuum:
$5 \times 16\frac{1}{2} \times 208 \times 9.18 = 157,529$
— grey water vacuum:
$2 \times 16\frac{1}{2} \times 208 \times 20.17 = 138,447$
— black water discharge:
$1 \times 10 \times 208 \times 0.83 = 1,726$
— grey water discharge:
$1 \times 27 \times 208 \times 3.28 = 18,420$
— cooling pumps:
$2 \times 8 \times 115 \times 24 = 44,160$
— total (watt-hours/day) = 360,282

Therefore, neglecting lighting, fan, power tools, etc., plus the increased current drawn by overloaded motors and short-duration starting currents, the estimated power consumption for the Yellow Elder Gardens station is about 360 kw-hr./day.

A2.3.3 *Actual Power Consumption:*
— At the time of this study there was no maximum demand meter installed at the Yellow Elder Gardens station.
— The daily power consumption based on the records for 28/2/72 to 28/6/72, was 415.8 kw-hr./day.

The error involved in the estimate (13.4 per cent) could be reduced if all contributing demands are considered.

A2.3.4 *Power Costs:*

A2.3.4.1 *Comments:*
In determinating estimated power costs it is necessary first to determine if maximum demand charges are applied in the location considered. If the maximum demand meters are the type which measure instantaneous demand, the cost estimate must be obtained by using the starting currents of the motors which create the heaviest demand. If they have a delayed measurement, and do not measure starting currents, it will be necessary to consider only the total demand of all equipment which may operate at one time.
Determination of the power consumption per day or year requires an estimate of the quantities of air and sewage (black water, gray water, or combined sewage) admitted to the system and the discharge rates of both the vacuum and sewage pumps. The average running times of the pumps then may be estimated, and the required power may be estimated from that data.
The Bahamas Electricity Corporation normally charges for electricity by total consumption (kw-hr.), and by instantaneous peak consumption measured in kilo-watts on a maximum demand meter. An estimate of the annual power cost for the Yellow Elder Gardens station, based on both the total and maximum demands, is included here as an example.

A2.3.4.2 *Calculations:*
— unit charge (based on actual use):
415.8 kw-hr./day × 30.44 days/month
= 12,657 kw-hr./month
12,657 × 12 months/year × 3.5 cents/kw-hr.
= \$5,315.94 (Bah.)/year
— maximum demand charge (based on estimate)
67.9 kw. × \$54.60 kw./year
= \$3,707.34 (Bah.)/year
— total charge
= \$9,023.28 (Bah.)/year

Therefore, the estimated power cost for the Yellow Elder Gardens station is about \$9,000.00 Bahamian dollars per year (about \$8,900 Canadian). The actual power costs include a fixed quarterly rate in place of a maximum demand charge and cannot be used for comparison.

A2.4 Maintenance and Operations

At the Yellow Elder Gardens collection station no detailed records are kept of daily maintenance work; however, records are maintained of user complaints and of breakdowns in the collection station equipment. In addition, the routine maintenance jobs are described in an operator's manual (ref. 1). The maintenance work involved in the installation therefore may be determined by considering these three sources of information. Certain routine operational jobs are also necessary and this requirement is discussed in section A2.4.4.

A2.4.1 *Summary of Complaints Registry:*
The following summary is based on records for the period May 1, 1971 to June 19, 1972:
— percentage of total number of complaints:
  — black water system = 66 per cent
  — grey water system = 34 per cent
— frequency of complaints:[1]
  — black water system, approximately $2\frac{1}{3}$ per week
  — grey water system, approximately $1\frac{1}{3}$ per week

[1]Personal observations by the authors suggest that the actual number of complaints may be in excess of the number recorded; however, one problem frequently results in more than one complaint and under such circumstances only the first complaint would be recorded.

Blockages in the black water mains were responsible for 27½ per cent of the total number of complaints. Approximately one-half of the problems were solved by the application of a mobile suction pump to the main at the clean-out immediately upstream of the blockage. With the rest of the main at atmospheric pressure the solid material causing the blockage (usually rags) can be drawn out. In some cases it is possible to increase the vacuum in the collection system, close off all mains but the one plugged, and admit a slug of air to the main upstream of the blockage, thereby forcing it through the main to the collection tanks. Only in rare cases is it necessary to remove sections of the pipe from the main. Where mineral deposits are suspected of contributing to the blockage problem, acid soaking of the main may remove the blockage.

Sixty-six per cent of all complaints (both black water and grey water systems) were due to problems involving private property. They included blockages, leaks, and mechanical breakdowns, but as repairs were the responsibility of the owners and for the most part were carried out by private contractors, the relative importance of each type of problem cannot be determined. It is expected that the two major problems involve foreign objects stuck in vacuum water closets or service laterals in the black system, and grease accumulation in the service laterals of the grey water system. Where the grey water service laterals are concerned, vacuum "pulling" of the pipes is attempted and, if that fails to remove the blockage, the owner is considered responsible for the required repairs. All repairs to black water equipment on private property (vacuum water closets and service laterals) are the responsibility of the owners; however, where a plugged or broken toilet valve causes a loss of vacuum in the system, repairs may be performed by the government maintenance crews. Problems involving private property demand an appreciable number of man-hours of crew time in locating the problems if not in correcting them.

The remaining 6½ per cent of the complaints involved other problems experienced with the vacuum sewer mains or collection station, such as leaks in the mains due to damaged pipe, collection equipment breakdowns, and temporary leaks of undetermined origin. Some problems involving grey water mains in 1971 were caused by the excessive length of one of the mains. The far end of it remained waterlogged because of an insufficient pressure differential. This problem was corrected by creating two mains from the original single main, thereby reducing the headloss in each line to an acceptable level.

A2.4.2 *Plant Breakdowns:*

As indicated above, the problems experienced with the vacuum collection station constitute only a small fraction of those encountered in the entire installation. Nine breakdowns were recorded for the period from October 19, 1971 to June 19, 1972, which is roughly one breakdown per month. The causes of these breakdowns may be summarized as follows:

Problem	**Number of Occurrences**
— failure of motor-to-pump coupling	2
— pump failure	3
— pipe blockage	1
— motor failure	1
— check valve failure	1
— loss of power (failure in electric power supply plus failure of stand-by generator)	1

A2.4.3 *Routine Maintenance Work:*

The following information was obtained from the Yellow Elder Gardens operator's manual (ref. 1) and from the experience of the vacuum sewerage foreman:

A2.4.3.1 *Daily:*

— check of pump grease caps and gland packing
(one labourer — ¼ hour)

A2.4.3.2 *Weekly:*

— pump maintenance (check and/or replacement of grease, gland packing, bearings) (one mechanic — 1½ hours)

A2.4.3.3 *Twice-monthly:*

— cleaning of grey water float-type valves (one labourer — 34 hours)
— cleaning of service liquid tank and heat exchange unit
(one labourer — 2½ hours)
— maintenance of electrical system
(one electrician — 1½ hours)

A2.4.3.4 *Monthly:*

— acid washing of black water lines
(one labourer — two hours)
(one foreman — two hours)
— cleaning of black water collection tanks
(one labourer — two hours)
(one foreman — two hours)
— maintenance of stand-by generator
(one electrician — one hour)
(one mechanic — one hour)
— maintenance of non-return valves
(one mechanic — 1½ hours)

A2.4.3.5 *Every Three Months:*

— cleaning of vacuum reserve tank
(one labourer — 1½ hours)
(one foreman — 1½ hours)
— cleaning of grey water collection tank
(one labourer — two hours)
(one foreman — two hours)

A2.4.3.6 *Every Six Months:*
— cleaning and repair of all pumps
(one labourer — 33 hours)
(one foreman — 33 hours)
(based on 11 pumps)

A2.4.3.7 *Yearly:*
— acid soaking of black water lines
(requires five labourers, foreman, and superintendent)
(seven men — three hours)
(two men — three hours)
— maintenance of grounds and buildings
(two labourers — 34 hours)

A2.4.4 *Routine Operational Work:*
Certain operations must be performed as part of the routine functioning of a vacuum sewer system. The following list was obtained from the Yellow Elder Gardens operators' manual and from practical experience:

A2.4.4.1 *Daily:*
— manual air admittance at the upstream end of the black water mains
(one labourer — ½ hour)
— readings of power consumption, pump running times, tank vacuums, sludge levels, etc., plus visual inspection of the plant
(one foreman — ¼ hour)

A2.4.4.2. *Weekly:*
— pumping of sludge from black water collection tanks, grease trap, and well head
(one labourer — 3½ hours)
(one foreman — 3½ hours)

A2.5 Cost Estimate — Personnel

A2.5.1 *Routine Operational and Maintenance Work:*
The items listed in section A2.4 are derived from operational experience in the Yellow Elder Gardens vacuum sewer system. The jobs are all routine operational and maintenance functions and are governed by the size of the system and the physical characteristics of the equipment used. Therefore, the time values obtained should apply to all vacuum systems of similar type and of the same size, regardless of location.

A2.5.2 *Non-routine Operational and Maintenance Work:*
The items listed below are rough estimates based on what is considered a typical, smoothly-operating system.

A2.5.2.1 *Daily:*
— administration and general office work
(one foreman — one hour)
— general maintenance work
(one labourer — one hour)
— system breakdowns (answering complaints, primarily concerning leaks and blockages in the mains)
(one labourer — one hour)
(one foreman — one hour)

A2.5.2.2 *Weekly:*
— system breakdowns (plant breakdowns)
(one labourer — one hour)
(one foreman — one hour)

A2.5.3 *Total Number of Man-hours Per Year:*
This estimate has been based on the assumption that the vacuum sewer system can be run by a full-time crew of two men, one foreman and one semi-skilled labourer. Therefore, a job requiring the work of two semi-skilled men for two hours was listed above as "labourer — two hr., foreman — two hr." rather than as "labourer — four hr.".
The items listed below are derived from sections A2.4.3, A2.4.4, and A2.5.2. Based on a five-day week and an eight-hour day, one man works 2,080 hours per year (replacements assumed for holiday periods). The total number of man-hours obtained from the estimates indicates that a two-man minimum crew is required to complete the work and that two men should be capable of running the station without working under inordinate pressure. The estimates also indicate that the work may have to be divided more equally between the labourer and the foreman or that the foreman may be able to operate more than one station. As indicated in section A2.4.3.7, it is essential that other members of the public works, or private contractors if necessary, be available to handle special tasks.

A2.5.3.1 *Man-hours per year — two-man full-time crew:*

1. daily
   — labourer 2¾ hr. × 260 days = 715
   — foreman 2¼ hr. × 260 days = 585
2. weekly
   — labourr 4½ hr. × 52 weeks = 234
   — foreman 4½ hr. × 52 weeks = 234
3. twice-monthly
   — labourer 36½ hr. × 2 × 12 months = 876
4. monthly
   — labourer 4 hr. × 12 months = 48
   — foreman 4 hr. × 12 months = 48
5. every 3 months
   — labourer 3½ hr. × 4 = 14
   — foreman 3½ hr. × 4 = 14
6. every 6 months
   — labourer 33 hr. × 2 = 66
   — foreman 33 hr. × 2 = 66
7. yearly
   — labourer 6 hr. × 1 = 6
   — foreman 6 hr. × 1 = 6
8. total man-hours (full-time crew)
   — labourer = 1,959
   — foremen = 953

A2.5.3.2 *Support from other personnel:*

1. weekly		
— mechanic $1\frac{1}{2}$hr. × 52	=	78
2. twice monthly		
— electrician $1\frac{1}{2}$ hr. × 24	=	36
3. monthly		
— electrician 1 hr. × 12	=	12
— mechanic $2\frac{1}{2}$ hr. × 12	=	30
4. yearly		
— labourers 12 hr. × 1	=	12
— superintendent 3 hr. × 1	=	3
— maintenance crew (labourer) 64 hr. × 1	=	64
5. total man-hours (support from other personnel)		
— labourer	=	76
— electrician	=	48
— mechanic	=	108
— superintendent	=	3

A2.5.4 *Cost Estimate:*
In obtaining a cost estimate, the wage received by labourers will be used as a base and the hours worked by others will be adjusted in proportion to their wages. For illustration purposes, the following values will be used (correct values may be obtained for each location):

— labourer	—	hours × 1.0
— foreman	—	hours × 1.3
— electrician	—	hours × 1.6
— mechanic	—	hours × 1.6
— superintendent	—	hours × 2.0

The number of man-hours per year, based on a labourer's wages, therefore are determined as follows:

— full-time labourer	— 2,080 × 1.0 =	2,080
— full-time foreman	— 2,080 × 1.3 =	2,704
— part-time labourer	— 76 × 1.0 =	76
— part-time electrician	— 48 × 1.6 =	77
— part-time mechanic	— 108 × 1.6 =	173
— superintendent	— 3 × 2.0 =	6
— total (man-hours/year)	=	5,116

If, for purposes of illustration, it is assumed that a labourer receives three dollars per hour, the annual cost in wages, for a smoothly-functioning system similar in size and type to the Yellow Elder Gardens installation, will be about $15,400.

A2.6 Cost Estimate — Other Operational Factors

A2.6.1 *Water Supply:*
There is no data available for water consumption at the Yellow Elder Gardens vacuum collection station. Tap water is used for cleaning tanks and equipment and for the vacuum pump service liquid. Groundwater is used as the cooling liquid in the heat exchange unit. Other arrangements may be necessary in other locations and costs should be estimated accordingly.

A2.6.2 *Vehicles:*
A half-ton or one-ton truck should be provided for the full-time use of each foreman and the cost of operating it will depend on local conditions. A scavenger truck ("honey wagon") is required for about $3\frac{1}{2}$ hours per week; preferably it will be supplied by the local public works department but the services of a private contractor may be necessary in some locations. Again, the costs should be determined for each particular installation.

A2.6.3 *Spare Parts and Consumable Materials:*
Scale formation in the black water mains of the Yellow Elder Gardens system necessitates 250 gallons of 20 per cent muriatic acid and 900 pounds of dry slaked lime per year. These materials may not be required in such quantities, if at all, in other installations. Other consumable materials include soap, rags, oil and grease, and disinfectant.
Since the government-owned vacuum sewer installations in the Bahamas are being rebuilt it is not possible to estimate the spare parts requirements which would result from normal operating conditions. Until better data becomes available it will be necessary to estimate cost of replacement parts from the life expectancies of the various pieces of equipment used.

Appendix III

Calculation of the Two-Phase Multiplier

1. air-to-water ratio at NTP = 2:1
2. pipe pressure (absolute) = 0.50 atmos.
3. volume correction for pressure change:

$$p_1 \; \upsilon_1 = p_2 \, \upsilon_2$$
$$1.0 \times 2.0 = 0.50 \times \nu_2$$
$$\therefore \; \nu_2 = 4.0$$

4. volume correction for temperature change:

$$\upsilon_1 \; T_2 = \nu_2 \; T_1$$
$$4.0 \times 510 = \nu_2 \times 528$$
$$\therefore \; \nu_2 = 3.86$$

5. air-to-water ratio at 0.50 atmos. and 50°F = 3.86:1
6. determination of air density:

$$\nu_1 \; P_1 = \nu_2 \, P_2$$
$$2 \times 2.42 \times 10^{-3} = 3.86 \times P_2$$
$$\therefore \; P_2 = 1.25 \times 10^{-3} \text{ slugs/ft}^3$$

7. fluid properties at 50°F and 0.50 atmos:

$$P_l = 1.940 \text{ slugs/ft}^3$$
$$\mu_l = 2.735 \times 10^{-5} \text{ lb.sec/ft}^2$$
$$P_g = 1.25 \times 10^{-3} \text{ slugs/ft}^2$$
$$\mu_g = 3.68 \times 10^{-7} \text{ lb.sec/ft}^2$$

8. calculation of terms:

$$\mu_l^{\frac{1}{4}} = 0.0723$$
$$P_l^{\frac{3}{4}} = 1.643$$
$$\left[P_l + \gamma P_g\right] = 1.940 + (3.86 \times 1.25 \times 10^{-3})$$
$$= 1.945$$
$$\left[P_l + \gamma P_g\right]^{\frac{3}{4}} = 1.651$$
$$x = \frac{3.86 \times 1.25 \times 10^{-3}}{1.945}$$
$$= 2.48 \times 10^{-3}$$
$$(1-x) = 0.9975$$
$$\left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right] = \frac{2.48 \times 10^{-3}}{3.68 \times 10^{-7}} + \frac{0.9975}{2.735 \times 10^{-5}}$$
$$= 43{,}250$$
$$\left[\frac{x}{\mu_g} + \frac{1-x}{\mu_l}\right]^{\frac{1}{4}} = 14.42$$

9. calculation of $Ø^2$:

$$Ø^2 = \frac{4.86 \times 1.651}{0.0723 \times 1.643 \times 14.42}$$
$$= 4.7$$

Appendix IV

Vacuum Sewer Systems in Canada as of Mid 1973[1]

A4.1 Projects Completed

1. C.S.S. RICHARDSON: Environment Canada Vessel, British Columbia — 2 vacuum toilets
2. C.S.S. STEWART: Environment Canada Vessel, British Columbia — 14 vacuum toilets
3. TRAILER: Marine Industries, Sorel, Quebec — 2 vacuum toilets, 2 urinals
4. TRAILER: Environment Canada, Fort Simpson, N.W.T. — 2 vacuum toilets
5. TRAILER: Canada Department of Public Works (rented), Toronto, Ontario — 2 vacuum toilets

A4.2 Under Construction

1. CAMPING AREA: Alberta Baptist Camp, Caroline, Alberta — 11 vacuum toilets, 2 urinals
2. CAMPING AREA: Travtel Recreation Ltd., Vancouver, British Columbia — 14 vacuum toilets
3. RESORT: Lake O'Hara Resort, Alberta — 27 vacuum toilets (to be expanded)
4. 2 TRAILERS: Ontario Ministry of Natural Resources — 12 vacuum toilets
5. TOBERMORY FERRY: Ontario Ministry of Transportation and Communication — 34 vacuum toilets

A4.3 Planned

1. Six more land-based installations
2. Five more marine installations
3. Four more trailers

[1]source: Vacusan Systems Limited, August 1973.

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